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Wireless Sensor Network for *Salicornia* plantation monitoring

Rede de Sensores sem Fios para Monitorização de Plantações de *Salicornia*

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Wireless Sensor Network for *Salicornia* plantation monitoring

Dissertation presented to the University of Aveiro to fulfill the necessary requirements for obtaining a Master Degree in Electronic and Telecommunications Engineering, under the scientific supervision of Professor Paulo Bacelar Reis Pedreiras and Professor Alexandre Manuel Moutela Nunes da Mota, both Professors at the Electronics, Telecommunications and Informatics Department at University of Aveiro.

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Palavras Chave

Internet das coisas, monitorização, sensores, redes de sensores, redes sem fios, microcontroladores.

Resumo

A *Salicornia ramosissima* é uma planta que cresce em ambientes salinos sendo famosa pelas suas características benéficas nas mais diversas áreas, tais como alimentação, medicina e biocombustíveis.

Na Universidade de Aveiro, um grupo de investigadores na área da biologia contribuiram para uma melhor compreensão do crescimento e desenvolvimento da *Salicornia* na Ria de Aveiro no que diz respeito à salinidade, fases de crescimento e sobrevivência.

No contexto da Internet das Coisas, as redes de sensores são um tema de estudo dado o vasto número de aplicações, pelo que, diversas tecnologias têm aparecido no mercado de modo a garantir qualidade de serviço aos seus clientes.

Foi assim proposto o desenvolvimento de uma solução que monitorize os parâmetros desta planta no seu habitat natural. Uma vez que este ambiente é selvagem e propício a roubos, os requisitos principais são: consumos energéticos e custos de desenvolvimento e implementação baixos.

Ao longo desta dissertação são apresentadas as tecnologias de redes de sensores actuais no mercado, bem como um estudo sobre os sensores necessários para a monitorização de uma plantação de *Salicornia* e o protocolo que favorece as necessidades da rede em questão.

Key words

Internet of Things, monitoring, sensors, sensors network, wireless sensor networks, micro-controllers

Abstract

The *Salicornia ramosissima* is a plant that grows in a salt-marsh environment and it has become famous because of their beneficial characteristics in several areas such as: human nutrition, biofuels and medicine.

At University of Aveiro, a group of biology researches contributed to a better understanding of a Salicornia population biology in Ria de Aveiro, especially aspects related to salinity, plant growth, and survival.

In the context of the Internet of Things, the wireless sensor networks is an emergent area of studies. Nowadays, there are several tecnologies in the market to answer the requirements and offer quality of service to the WSN's users.

It was proprosed a solution to monitor the *Salicornia* parameters in their natural habitat. Once the habitat is considerer wild, it is conducive to theft. Because of that, the main requirements for this network are to create a low cost and low power consumption network.

Along this dissertation, are presented and discussed some emergent wireless tecnologies in the market, as well a discussion about the sensors needed to monitor the *Salicornia* plantation and the communication protocol which answers the needs of the network.

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Acronyms

ACK	Acknowledge
ADC	Analog to Digital Converter
AES	Advanced Encryption Standard
ARQ	Automatic Repeat Request
ASK	Amplitude-Shift Keying
ANACOM	Autoridade Nacional de Comunicações
CPU	Central Processing Unit
DMA	Direct Memory Access
DSN	Distributed Sensor Network
DSSS	Direct-Sequence Spread Spectrum
EEPROM	Electrically Erasable Programmable Read-Only Memory
ERP	Effective Radiated Power
FEC	Forward Error Correction
FIFO	First In First Out
FSK	Frequency-Shift Keying
I2C	Inter-Integrated Circuit
IC	Integrated-Circuit
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISM	Industrial, Scientific and Medical

LAN	Local Area Network
LPWAN	Low-Power Wide Area Network
LTE	Long Term Evolution
MAC	Medium Access Control
MSK	Minimum-Shift Keying
NB-IoT	Narrow-Band - Internet of Things
NIST	National Institute of Standards and Technology
NTC	Negative Temperature Coefficient
OFDM	Orthogonal frequency-division multiplexing
PM	Power Mode
PSK	Phase-Shift Keying
QoS	Quality of Service
RAM	Random Access Memory
RF	Radio-Frequency
ROM	Read-Only Memory
RTD	Resistance Temperature Detector
RS	Rural Scenario
RX	Receiver
SI	Système international d'unités/International System of Units
SIG	Special Interest Group
SoC	System on a Chip
SPI	Serial Peripheral Interface
STEM	Sparse topology and energy management
TI	Texas Instrument
TX	Transmitter
UART	Universal asynchronous receiver/transmitter
US	Urban Scenario
WSN	Wireless Sensor Network

1

Introduction

1.1 Motivation

The *Salicornia Ramosissima*, as shown in the Figure 1.1 is a plant that grows in salt-marsh environment and it became famous because of their potential use in several areas such as: human nutrition, biofuels and medicine. At University of Aveiro, a group of biology researchers [1] [2] have contributed to a better understanding of a *Salicornia* population biology in Ria de Aveiro, especially in aspects related to salinity, plant growth and survival. Ria de Aveiro is a shallow coastal lagoon formed by many channels with zones of mud flats and salt marshes which meets all conditions for a wide production of the *Salicornia*. To make possible a healthy and productive plantation is necessary to ensure the adequacy of water parameters. This way it was proposed to define a solution to acquire and process data from several sensors spread along the coastal lagoon.

The term Internet of Things (IoT) is a concept that includes several technologies with a purpose to connect real-world objects, such as temperature, humidity and acceleration sensors

Figure 1.1: *Salicornia Ramosissima* in two different stages [1]

to Internet. Wireless Sensor Network (WSN)s have an important position in IoT, acting as a source of data. It's expected that in 2020 around 50 billion [3] of small devices will be connected and digitalizing information to the Internet, which combined with the new knowledge of "big data", will create the framework for many new types of applications.

The IoT concept has attracted the attention for embedded systems since the electronic devices that incorporate microcontrollers simplify its design and provide flexibility. The use of a microcontroller device facilitates making modifications or adding new features. Afterwards only an update of the software is needed. This means that embedded computers fit the needs of a WSN very well, once it includes a microcomputer to perform specific dedicated applications.

Many technologies in the context of IoT [4] [5] have been developed for several applications, such as smart energy usage, senior home-care, transportation and smart agriculture. Depending on the conditions and environments where a sensor network is deployed there are many features to take into consideration, like energy consumption, costs, communication range, scalability, security and reliability.

With IoT a bunch of solutions appeared, which gave to developers a lot of possibilities. It is part of the motivation of this dissertation to do a research about the protocols and technologies that IoT concept brought. Moreover to develop a wireless sensor network solution, tailored for the specific needs of *Salicornia* cultures at Ria de Aveiro.

1.2 Objectives

The purpose of this dissertation is to find an efficient solution and develop a distributed wireless data acquisition system specified for agriculture application. Consequently, the objectives of this dissertation are:

- Benchmarking and research upon of emerging technologies related with IoT agriculture applications;
- Study of the Medium Access Control (MAC) protocols for WSN;
- Design and implement a communication protocol between the CC1110 devices;
- Test range and quality data transmission of 433MHz wireless communication with transceivers CC1110 from Texas Instrument (TI) [6] devices in lagoon environment;
- Data acquisition from sensor nodes;
- Evaluate the performance of WSN implemented within the communication protocol;

1.3 Document Organization

This dissertation is organized as follows:

Chapter 1 contains the motivation and general project objectives.

Chapter 2 briefly describes the main characteristics of *Salicornia* plant, survival and growth studies done by biology researchers at the University of Aveiro. In addition, the project requirements are also described, as well, the sensors needed.

Chapter 3 presents an overview about the WSN structure, specifying each layer, with focus on the physical, data-link and network layer. In addition, some wireless technologies used in WSN's are described and compared. Finally, an overview about the embedded systems and their main features are briefly explained.

Chapter 4 presents the proposed architecture as well as the communication protocol and data acquisition process.

Chapter 5 provides a detailed explanation of the proposed architecture including the software implementation.

Chapter 6 contains the results of the evaluation tests done.

Chapter 7 presents the conclusions and some future work efforts to complement the project of this dissertation.

2

Principles of *Salicornia* plantation monitoring

2.1 Introduction

This chapter presents an overview of the main concepts regarding the scope of this dissertation, which is monitoring a *Salicornia* plantation, thereby the chapter is divided as follows.

Section 2.2 presents a short introduction to the *Salicornia* plant and its characteristics in order to understand the parameters that need be monitored. In addition, the main objectives and requirements are described.

Section 2.3 starts with an overview of the main features of general sensors, followed by a detailed description of different sensors that are needed to monitor the *Salicornia* plantation.

Section 2.4 presents a short research about related work in agriculture sensors applications.

2.2 *Salicornia*

Though the aim of this dissertation is not to do a deep study about *Salicornia* growth and survival, it is important to understand which are the requirements and characteristics of it to make an efficient system that can monitor a large plantation.

Biology researchers from the University of Aveiro have monitored a small plantation of *Salicornia* in Green Houses for a period of two years, to evaluate the behavior of this plant. In their research paper [1] are mentioned and explained the different parameters, as well the different environment scenarios that were controlled in the Green House. The *Salicornia* plant subsists in salt-marsh conditions which change constantly given the tidal flooding, evapotranspiration, and vegetation. These conditions affect the chemical and physical factors of the plant survival. Parameters such as salinity, temperature and humidity are the ones with more impact in the plant growth and survival, and because of that they are the most important to be monitored in the plant natural habitat. Other parameters, like CO_2 and detection of possible high metal contamination, are only tested in a controlled Green House. Until now, to monitor the *Salicornia* plantation, in their natural habitat, biology researchers periodically collect some water samples from lagoons and then, study them in the laboratory. To obtain more precise conclusions about the environment changes, it is necessary to collect more data. This drives to a wireless sensor network which allows to monitor the *Salicornia* parameters.

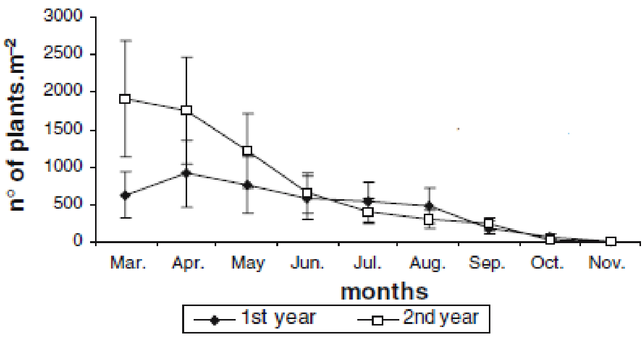


Figure 2.1: Mean *Salicornia* density over two years in a Green House [2]

A high density of *Salicornia* is observed between March and July, as it is presented in Figure 2.1. The soil conditions change during seasons and thus their characteristics also change. After June the soil becomes too dry which makes the measurements of salinity and other soil moisture parameters difficult.

In the real habitat, the conditions vary constantly, which brings an engineering challenge, given the difficult environment conditions to deploy a sensor network along the lagoon.

2.2.1 Project Requirements

In order to successfully answer to the user needs, the project objectives are described.

• Find an efficient solution which allows collecting sensors data, which are spread along the lagoon area.

• The collected data must be available on a remote platform.

• A low cost solution and low power.

Some specific requirements are also presented:

• The total plantation area is around $19000m^2$. The total area is divided into small areas, around 1100 m^2 each. Dividing the total area into the small areas, at least, seventeen nodes are needed to cover all the *Salicornia* plantation.

• The data from sensors should be updated every hour with the identification of the area which is being covered.

• The implemented system must be fully operating for, at least, a period of six months, to cover the seasons with high-density production of *Salicornia*.

It is important to clarify that the *Salicornia* plant and their growth and survival characteristics are still being studied. A study in a Green House is not enough to conclude about the healthy production of the *Salicornia* plant in their natural habitat. Thus, the range of the different parameters that must be monitored is not precisely known. Table 2.1 and 2.2 present the average range values of salinity in Ria de Aveiro and temperature in Aveiro region.

	MIN	MAX
Salinity(NaCl/l (%))	10	90

Table 2.1: Range of Salinity values in Ria De Aveiro [2]

	MIN	MAX
Temperature in Aveiro (°C)	-3	37

Table 2.2: Maximum range of temperature values in Aveiro [7]

2.3 Sensors

Sensors allow to acquire data to monitor the *Salicornia* plantation. It is thus essential to identify which sensor can measure the desired parameters. Before integrating them it is necessary to study how they operate, the variety of types that exist and the advantages each one offers. A deep study must be done to save costs, facilitate the implementation, allow flexibility and durability. The sensor types range is vast and they can be categorized in different ways [8]. Based on [9] they can be organized as shown bellow:

- **Passive, Omni-directional sensors:** They measure a physical quantity without manipulating the environment. They are self-powered once energy is only needed to amplify the analogue signal.
- **Passive, narrow-beam sensors:** Operate as the ones presented before, but they have a well-defined measurement direction.
- **Active Sensors:** are defined by actively probing the environment.

Each of these sensors have different uses with individual peculiarities. When selecting a sensor it is important to take into consideration the accuracy, dependability, energy consumption, cost, and size.

Following these considerations and knowing the range of values of each target environment variable a study of the salinity, humidity, and temperature sensors is presented bellow:

Salinity Sensors

Salinity is the amount of dissolved salts contained in a given volume of water [10].

It is important to find an accurate sensor that respects the range of salinity in the *Salicornia* habitat, which is presented in Table 2.1. Salinity can not be measured directly, is commonly done by using conductivity or optical processes.

The simplest way to acquire salinity levels is done by measuring the conductivity of the water. In [11], authors proposed a low cost sensor to measure the water conductivity. A simple and not expensive option to measure the conductivity is done by using two pieces of a conductive material placed at a given distance and obtain the electrical resistance between them. It is known that the electrical resistance of water decreases as salinity increases. Temperature has impact in the conductivity measurements, which requires a calibration between the electrical resistance, temperature and volume of the solution to obtain the salinity. However, the conductivity method is susceptible to faster corrosion because of the materials used, as well to the interference of other substances in the conductivity measurements.

Optical sensors offer some advantages in terms of durability compared with conductivity sensors but are more complex and expensive. Optical techniques, as presented in an experimental research [10], normally use a refractometer to measure the fiber refractive index to obtain the salinity of a solution. This measurement is done based on the resonant coupling of the light guided by a single-mode fiber, which waves depend on the refractive index of the outer medium [12]. Effects as temperature and pressure can also cause interference on the measures in this technique.

Sensor	Manufacter	Output	Measuring Surface	Durability	Price €
Probe K 0.1	Atlas scientific	Conductivity(V)	Graphite	~10 years	195 - 206
Soil Moisture	SparkFun	Resistivity(V)	N/A	N/A	5

Table 2.3: Sensors to measure salinity

Comparing optical sensors with conductivity sensors, the first ones are more inherent to electromagnetic interference, having a compact size, high sensitivity, low noise, long distance sensing and high durability against corrosion. Nowadays, optical techniques are very used in smart sensing.

In terms of price, a typical conductivity sensor costs around 5 euros, as mentioned in Table 2.3, but one with high accuracy costs around one hundred euros. Optical sensors are still more expensive compared with conductivity sensors. There is still a lack of information about the accuracy that an optical sensor provide, but in terms of costs, they are very expensive. The compared prices are available on [13] [14].

In conclusion, to obtain the salinity measurement, by optical or conductivity techniques, is required an algorithm to calibrate the salinity measurements. This calibrations brings complexity and extra costs, to obtain precision on the results. In others words, measuring salinity, is an engineering challenge, which ask for new techniques and processes to facilitate the integration and viability of the sensor.

Temperature Sensors

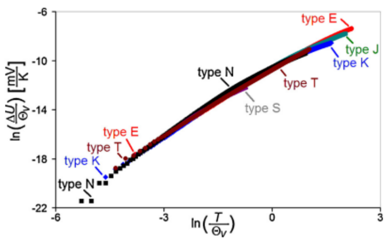
Temperature sensors measure the amount of heat or coldness that are generated by an object or system [15]. Along the years, different scales to measure the temperature were proposed. Kelvin(K) is the measurement unit defined by Système international d'unités/International System of Units (SI) for the temperature. Besides Kelvin, in engineering and science, Celsius(^{o}C) is another scale often used to represent the temperature.

Temperature sensors differ in terms of the measurement range, precision, accuracy, and resistance. In [15] and [16], sensors are divided into two groups: **Absolute sensors**, where the temperature measured is refereed to the absolute zero or other point on the scale, and in **Relative Sensors**, where the temperature is obtained by the difference between two objects, where one is the reference point. Temperature sensors can be categorized into four groups.

Thermocouple sensors are based on *Seebeck Effect* [1]. The total electromotive force generated between two different metals is proportional to the temperature difference between the two junctions.

The most common metals used are nickel, copper, and chromium. Each metal offers different ranges of sensibility and linearity. These differences are usually categorized into different types of thermocouple sensors, as shown in Figure 2.2b, producing different temperature ranges. Knowing the Seebeck Coefficient of each metal, it is possible to select the ones that best fit the range that has to be measured. These sensors require a conversion process of voltage in temperature values. This conversion can be obtained through a conversion table given by the sensor provider or by a polynomial approximation method standardized by National Institute of Standards and Technology (NIST). These sensors offer a wider range, between -200 to 2315 ºC [17]. Given their proprieties, as range and durability, they are usually applied in industrial environments. Depending if they are encapsulated, or not, the prices vary from 10 euros to 500 euros each one [18].

(a) Thermocouple sensor (E52-CA6DN)



(b) Universal function of emf vs. T and characteristic temperature [19]

Figure 2.2: Thermocouple sensor

Resistance Temperature Detector (RTD) These sensors belong to the group of thermo-resistive sensors. They consist of a wire wrapped with a ceramic material. The operating principle of these sensors consists of the variation of the resistance with temperature. The most used metals on this kind of sensors are nickel and platinum which offer better quality in terms of linearity, presented in Table 2.4. The family of RTD named PT100 sensors, represented in Figure 2.3 is one of the RTD most commercialized sensors[16], and it is the one, which offers higher range because of the good behavior of platinum behavior in temperature variations. Depending on the resistance, they can offer a range between -200 to 600ºC [17]. The conversion of resistance to temperature can also be done by tables available from the sensors providers or by polynomial approximation which increase the complexity of the conversion. The RTD sensors are absolute sensors, because the measurement depends on the references table .

[1] At the junction of two different types of wire, heat is directly converted to electricity.

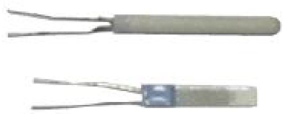


Figure 2.3: RTD sensor (PT100)

Sensor	Range °C	Accuracy	RTD Material	Price €
PT(100)	[-200 550]	± 0.5°C	Platinum	12
Ni(120)	[-60 250]	± 0.5°C	Nickel	3 - 7

Table 2.4: RTD Sensors most commercialized [20]

Thermistor results from the words *thermal* and *resistor* [15], and they are based on semiconductors. These sensors result from the variation of the resistance. The Negative Temperature Coefficient (NTC) sensors, are the thermistors that offer more precision. Decreasing the temperature, the resistance will also decrease. This results in a negative coefficient. The most used semiconductors used in thermistors are cobalt, iron, magnesium, copper and titanium and then encapsulated with ceramic materials. NTC sensors have a non-linear response which brings some disadvantages in terms of the conversion of resistance into temperature. They usually operate in a range between -100 to 300 °C [17]. Thermistors are absolute sensors, as the temperature measurement is refereed to an absolute-temperature scale. In terms of price, these sensors are known for a low price.

Figure 2.4: NTC sensor(USUR1000-503H)

Integrated-Circuit (IC) [21] sensors are based on the operating principle of a *Brokaw Cell* [2] . It is a simple voltage reference circuit, which is easily implemented in an IC. The conversion of current or voltage to temperature is quite simple once they are proportional between them. These characteristics offer a high linearity which is one of their biggest advantages.

Digital temperature sensor or also called smart sensors, are based on a circuit front-end, as the Brokaw Cell, and an Analog to Digital Converter (ADC), as shown in Figure 2.6. The measurement precision depends on the ADC resolution. The most common digital interfaces in smart sensors are I2C and SPI.

[2] Consists in a circuit with a N number of transistors. The voltage V_{be} is proportional to the absolute temperature. The final current is divided by the N number of transistors in parallel.

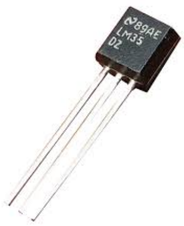


Figure 2.5: CI sensor(LM35)

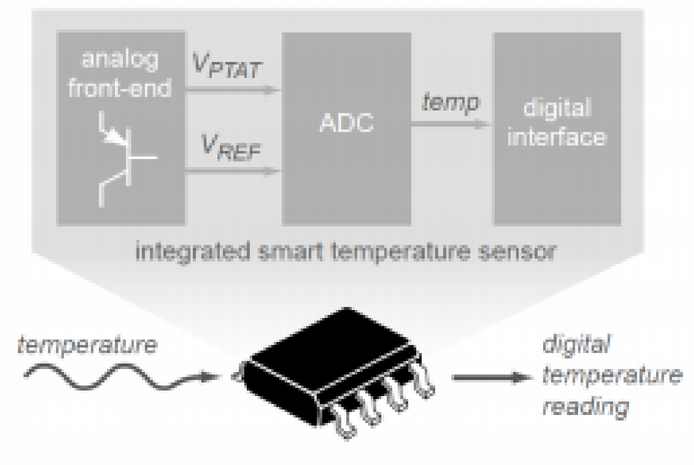


Figure 2.6: Diagram of an integrated smart temperature sensor.[22]

In terms of integration and deployment of a solution, digital temperature sensors brings several advantages, if compared with the others presented before. The main disadvantage of these sensors, as the thermistors sensors, is the limited range, between -50ºC and 150ºC [21], once both are semiconductors materials. Table 2.5 presents different digital sensors and their characteristics and price. In terms of current consumption, depending on the sensor, it can offer different power modes, active, when is doing the data acquisition or in standby, allowing very low power consumptions.

Sensor	**Manufacturer**	**Accuracy**	**Output Type**	**Consumption**	**Price (€)**
AD592ANZ	Analog Devices	± 2.5ºC%	Current	N/A	3.02 - 5.33
DS18B20	Maxim Integrated	±0.5ºC	Digital	750 nA (standby mode), 1.5 mA (active mode)	2.33 - 2.36
LM35	TI	±0.5ºC	Voltage	60 mA (active mode)	0.67 - 1.37
LM70CIMM	TI	±1.5ºC	Digital	470 uA	0.71

Table 2.5: IC temperature sensors [23] [24] [25] [26]

Depending on the final application, each sensor offers different advantages. If it is necessary to obtain results between a high range, thermocouples and RTD sensors, are the most suitable. In terms of saving costs, thermistors are less expensive. The main disadvantages of these sensors are their complex algorithms, the electrical components must be added, and their calibration. The sensors based on semiconductors offer more resistance to its degradation. In other hand, IC sensors are the most efficient in terms of implementation, offering a system plug and play combined with communication protocols, which directly communicates with a microcontroller.

Humidity Sensors

Humidity determines the amount of water vapor present in a gas or moisture. The most common used measurement unit is the Relative Humidity (RH) [15].

In the context of the *Salicornia* application, it is important to measure the air and the soil moisture. There are two concepts about the humidity measurement. If talking about the *moisture*, it generally refers to the water content of any material applied to liquid and solids. On the other hand, *humidity* refers to the water content in gases. There are different types of humidity sensors and the most common are named as capacitive and resistive [9].

Capacitive Sensors operating principle consists in a phenomenon of attracting and holding water molecules from the surrounding environment named by *Hygroscopic*. This phenomenon allows that a capacitance is formed between two metalized electrodes placed at opposite sides. In other words, a dielectric material between a pair of electrodes form a small capacitor [9]. The capacitance is integrated on a resonant circuit where the sensor is the capacitive element and the frequency response varies with the capacitance. The operating principal shows that increasing the humidity of moisture the dielectric constant will also increase.

Resistive Sensors are based on the general concept of a conductivity sensor. A low resistivity material is used, which changes significantly with humidity conditions. The common composition of a conductivity humidity sensor is: two electrodes placed close to each other, under a substrate, and both connected to a terminal. The humidity measurement results of the resistance between electrodes.

Although the materials and composition of humidity/moisture sensors for air and soil measurements differ, the operating principles for capacitive and resistive sensors are the same.

In Figure 2.7 examples of sensors to measure the soil moisture are shown, both resistive and capacitive. These sensors offer an operating ranger lower than the ones presented before, from -40°C to 60°C [27] and a range between 0 and 45% RH. The corrosion of the electrodes results in a short period life span of these sensors.

In Figure 2.8 a capacitive and resistive sensor to measure the air humidity [28] are shown. The HS1101LF operates between -60°C to 140 °C and a humidity range between 1 and 99% RH. In other hand, an example of a resistive humidity sensor, the HCZ-D5 sensor [29] only operates between 0 to 100°C and a humidity range between 1 to 90 % RH.

Between these two types of sensors, capacitive or resistive sensors, their price can go from around ten up to hundreds of euros.

In other hand, digital humidity sensors also brings several advantages, as temperature ones mentioned before. Integrated circuits bring simplicity to sensors integration, a range between

(a) Capacitive Humidity sensor [HS1101LF]

(b) Resistive Humidity sensor [HCZ-D5]

Figure 2.7: Examples of humidity sensors to air measurements [20]

(a) Capacitive moisture sensor [Vernier]

(b) Resistive moisture sensor [WATERMARK]

Figure 2.8: Examples of moisture sensors to soil humidity measurements [20]

-50 to 120 °C, and a humidity range between 0 to 100 % RH. In Table 2.6 are presented the most commercialized sensors, which also include temperature measurement.

Sensor	Manufacturer	Accuracy	Consumption	Price €
BM1280	Bosch	±3% RH, ±0.5°C, ±0.2Pa	3.6 uA	3.7 - 7.6
HTU21D	TE Connectivity	±0.4°C, ±2 RH	14uA (standby mode), 500uA (active mode)	1.9 – 5.7
Si7006-A20	Silicon Labs	±1°C, ± 5% RH	150 uA (active mode), 60 nA (standby mode)	1.2 - 1.4
HDC1000	TI	±0.2°C, ± 3% RH	1.2 m A (active mode), 200 nA (standby mode)	2.9 – 5.3
SHT2	Sensirion	±0.3 °C, ±3 % RH	385 uA	1.66 – 2.73
HTS221	ST	±0.5 °C, ±3.5 % RH	2 uA	1.53
DHT11	Adafruit	±0.5 °C, ±5 % RH	2.5mA	7.96 – 9.95

Table 2.6: Temperature and humidity digital Sensors

If developing a low power solution, the power consumption of each sensor, is very important. These sensors, already comes with low power features, such as active and standby modes, increasing their efficiency. IC sensors shows to be the best option, in terms of cost and simplicity, if the requirements of range and accuracy respect the needs of the application.

2.4 Related work on WSN's for agriculture applications

Many WSN applications have appeared over the last years. Precision agriculture, environment control and biodiversity mapping have grown exponentially with cost reduction and sustainability increase.

Nowadays there is a trend to increasingly use sustainable agriculture techniques, due to the visible degradation of large farmland areas over the past years. It is also required to control the environment, with respect to chemical pollutants. It is important to understand the behavior of plants and animals over different conditions and habitats. All these aspects brought the need for new sensors that allow measuring the parameters that each application demands.

The most common WSN application in agriculture, is a system to monitor and control the irrigation since this process is expensive. Thus, it is important to know which fields need additional watering or not. They are also used in vineyards to control the environmental changes that may alter the value of the crop and how it is processed. Another application is in tracking animals with sensors placed on each one [9] [30].

Figure 2.9: Applications of Wireless Sensor Networks to agriculture and environment control [31]

In the very recent years, many applications and technologies have emerged in regard to environment sustainability.

Smart sensors, defined as devices with small memory and processing capabilities that perform many operations like accurate sensing, ranging, signal conditioning and calibration, are growing in the market, which creates opportunities for developers for a wide bunch of solutions with high quality and easy of implementation. There are diverse solutions on the market, which allow measuring different parameters, according with the customers needs.

Some commercial application which are already in the market for more than two years will be presented bellow. These applications include the data acquisition and analysis which is available on the web, offering to the customer updated information at any time.

Winegrid [32]: is an application to monitor the winemaking process of barrels or tanks. It offers several sensors such as temperature, density, turbidity and level. All these parameters can be monitored through a web platform in real-time. The aim of these applications is to reduce the costs and time consumption to analyse each barrel of wine.

WaterBee [33]: is an intelligent irrigation system that collects data about soil moisture and other environmental factors. They offer full service to the customer with an implementation of the sensors nodes, maintenance, and real-time data. They provide a system that can be adapted according to the user's situations and business objectives using machine learning approaches.

SmartBob [34]: is a management system of monitoring powders and bulk solids for networks of bins, tanks or silos. These commercial applications allow controlling high or super-high temperatures and measuring submerged solids. They offer several Accessories, Consoles, and Softwares depending on the needs of the customer .

Check it Now [35]: is a cloud service that provides a monitor system to control several parameters of the agriculture environments through a smartphone application or personal computer. They also offer a historical record about the previous measures. They have some applications available and specially designed to monitor and control environments such as: potatoes plantations, grains conditions, and bins growth .

The [36] work, is an example of a WSN project specially designed to monitor with precision, irrigation agriculture plantations. It explains the challenges in an irrigation process for large production areas, since the sensors and communication challenges of the network.

In the following chapter, another network features will be discussed, in order to show, how to become more efficient the development and deployment of a WSN for a specific application.

2.5 Chapter Considerations

This chapter presents a brief description about the *Salicornia* plant, and the main requirements to efficiently monitor its parameters, which are salinity, humidity, soil moisture and temperature.

Taking into consideration these requirements, it is important to do a research about which sensors are available on the market, and conclude about which one allows to accurately measure the *Salicornia* parameters.

To obtain the salinity measurement, it is common to use conductivity sensors, which requires an algorithm to process the output voltage into salinity as well as a calibration process. It brings complexity to the sensor integration. As disadvantage, precise conductivity sensors are expensive, and suffer fast corrosion in salinity environments. Given the environment conditions, the best measurement option, would be an optical sensor, which offers more durability and accuracy. However, given the water turbidity, it is not expectable to obtain precise results. In addition, optical sensors are expensive. As conclusion, the integration of a salinity sensor in *Salicornia* habitat brings a challenge in terms of guaranteeing an efficient performance, durability and low cost integration.

For temperature and humidity, there are several options in the market, which answer the *Salicornia* environment needs. A digital sensor, which can measure both parameters, brings simplicity to sensor integration, for a low price. However, to measure the soil moisture, the same problem is presented, as the salinity. It is not viable to integrate sensors, which suffer fast corrosion.

Besides the market offer some solutions, as presented in Section 2.4, an oriented solution need to be proposed to answer the specific needs of *Salicornia* plantation.

To conclude, this chapter shows that one of the main challenges to monitor *Salicornia* plantation, is to find sensors which answer its needs.

3

State of the Art

3.1 Introduction

The purpose of this chapter is to introduce important concepts used in the scope of this dissertation. Therefore the topics are divided as follows:

Section 3.2 presents an overview about WSN's in an IoT concept, describing each layer of their network architecture.

Section 3.3 presents a result of a research about the emerging wireless technologies applied in WSN's in the recent years.

Section 3.4 describes the sensor node specifications, in terms of hardware performance to deploy in IoT context. It explore the evolution of embedded systems and the advantages it brings to WSN's.

3.2 Wireless Sensor Networks

3.2.1 Overview

Wireless Communication Network is defined as a wireless network with devices spatiality distributed which have the functionality to receive and send useful information from a specific environment[37].

These networks have a long history starting with the World War I. The army used wireless communication networks to connect them to strategic points by an amateur radio system [30]. In Figure 3.1 a structure of messaging is visible, passing between the army headquarters up to the national guards creating a tree network.

Later, a program named Distributed Sensor Network (DSN) was developed to explore the challenges of implementing distributed/wireless sensor networks. Soon partnerships were created between universities, to research about wireless sensor networks enabling applications such as air quality monitoring, forest fire detection, and waste-water detection.

In recent years, WSN's become even stronger in markets due their advantages in terms

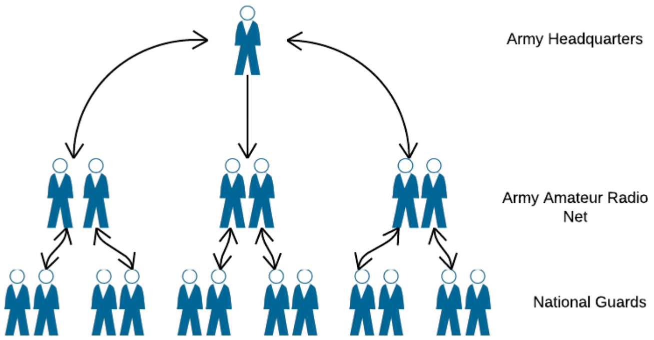


Figure 3.1: Basic system of a tree wireless network to army application

of size, price, flexibility and distributed intelligence into networks implementation and deployment. Wireless solutions allow the implementation of protocols which provide auto configuration, and set up of new sensor nodes, offering simplicity and feasibility in the network installation. For environments, as the army network example, wireless networks are the most efficient option, where cabling is impossible or of difficult installation. Wired are very reliable and stable, but they are expensive because of the cabling cost and their installation.

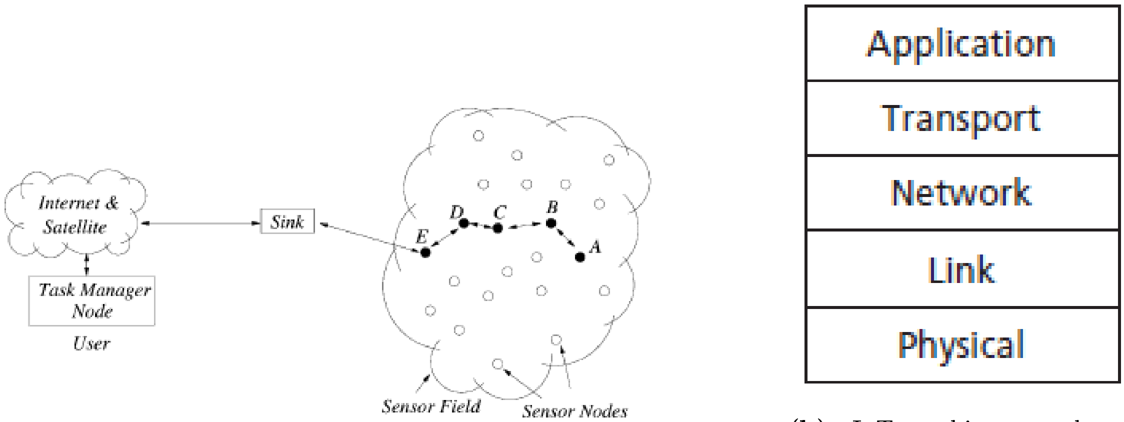
3.2.2 WSN Architecture Layers

Any network is based on an architecture, usually divided by layers. Based on [37], Figure 3.2a presents the sensors field with several sensor nodes scattered around it. Each sensor node has the capability to collect data and route it to the Sink. A sink node is also called Base Station and it has the functionality to interact with the sensor nodes and the user. Figure 3.2b, represents the five layers protocol structure used in almost all networks. While traditional networks focus to achieve high quality of service(QoS), WSN's must focus primarily on power consumption. According with [37], a perspective is presented on how these five layers are arranged to wireless sensor networks and a brief explanation about each layer is also given.

Physical Layer

The Physical layer takes care of the frequency selection, carrier frequency generation, signal detection and modulation.

As mentioned before, wireless communication use the radio spectrum to communicate over the air. Figure 3.3 shows the limited radio spectrum range from 3kHz-300GHz, which is divided in small frequency sections, called bands. They are categorized into longwave, mediumwave and shortwave radio frequencies. Once divided in small bands, they are divided into commercial or military/governmental bands. This way, some bands are completely restricted, other requires a licence to use them, and other are unlicensed. In terms of frequency selection, WSN's usually use unlicensed ISM bands. Unlicensed or license-free, means that the user does not need an individual license from the telecommunication regulatory authorities. However, if using ISM bands, there are some regulations which must be respected such as the restrictions with the output power transmission, limited duty-cycle and bandwidth. Figure 3.4 presents



(a) Sensor nodes scattered in a sensor field [37]

(b) IoT architecture layers based on [37]

Figure 3.2: Example of a WSN topology and architecture layers

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the frequency bands, the restriction of the Duty Cycle and Effective Radiated Power (ERP) allowed in Europe [38].

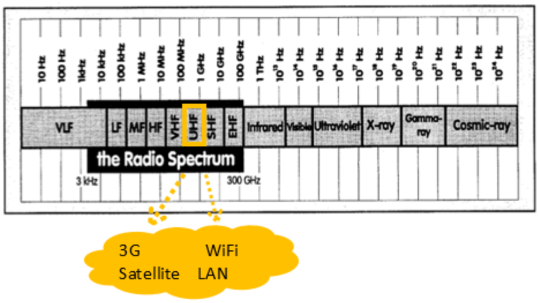


Figure 3.3: Radio Spectrum

In Portugal, Autoridade Nacional de Comunicações (ANACOM) is the authority responsible for the regulation of communications to ensure the efficient management of radio spectrum, among other responsibilities. In [39], ANACOM specifies the reservations of frequency bands and their maximum power limits, for example, in article 5, they specify the free usage of the band 433.05-434.79 MHz for industrial, scientific, and medical applications. These bands demand a power density limitation of -13dBm/10kHz for using bandwidths above 300kHz. In order to respect the duty-cycle limitations, they must be assured by adequate techniques, such as Adaptive Frequency Agility (AFA), non-depending on the user.

The frequency generation and signal detection depends on the radio that developers will choose, which also offers different modulation schemes. Section 3.4 gives an overview about the sensor node requirements and its main features.

In terms of modulation [40], several digital techniques have been implemented in wireless communications. These techniques ensure high data rate transmission, data security

Frequency Band	Field Strength	Duty Cycle	Channel Bandwidth
433,05 – 434,79 MHz	10 mW e.r.p.	No limits	≤ 25 kHz
863-870 MHz	≤ 25 mW e.r.p.	No limits	≤ 25 kHz
2400-2500 MHz	10 mW e.r.p.	No limits	Entire band

Figure 3.4: Frequency ISM bands for a Non-Specific Range in Portugal regulated by ANACOM [39]

and quality of the signal. Due to their simple architectures, digital modulation offers a low power consumption without performance degradation. The techniques Amplitude-Shift Keying (ASK), Phase-Shift Keying (PSK), and Frequency-Shift Keying (FSK) are the base of digital modulation and demodulation to wireless communications. While ASK offers simplicity and lower power consumption, FSK and PSK offer more advantages in terms of bandwidth and reliability.

Data Link Layer

This layer is responsible for multiplexing the data streams, data frame detection, medium access control and error control. It is responsible for ensuring reliable communication between the node devices [9].

MAC protocols solve the simple task of coordinating the instants when a certain number of nodes accesses the shared communication medium in order to reduce the overhearing, collisions, overhead and idle listening.

In [41], the authors present the evolution of MAC protocols and they detail all requirements and features to design a specific MAC protocol for a WSN. They classify WSN MAC protocols into four categories: asynchronous, synchronous, frame-slotted, and multichannel.

Asynchronous MAC protocols focus on how to efficiently establish communication between two nodes that have different active/sleep schedules.

In **Synchronous** protocols neighbouring nodes are synchronized to wake up at the same time to communicate between each other. The focus of these protocols is the delay reduction and throughput improvement.

Frame-slotted mechanisms allocate time slots in a way that two neighboring nodes within the two-hop communication are not assigned to the same slot.

Multi-channel protocols provide multi-task support, static and dynamic channels allocation, to handle higher traffic situations. Static channels are optimized for star and tree topologies, where nodes communicate in different channels. In other hand, allocation with dynamic channels are not preciously selected.

In the scope of this dissertation it was tailored an asynchronous approach, as the amount of information is very low and the sensor nodes should operate for extended periods. An efficient way to establish communications between the nodes must be formulated. Nodes alternate between active and sleep modes and periodically wake up for a short duration and go immediately to a sleep mode after receiving/sending the packet. As a result, the idle state is avoided and energy is conserved. A small duty-cycle brings advantages once it decreases the possibility of collisions between the neighboring nodes and the coordinator node. One example of asynchronous MAC protocol is presented below [41]:

Sparse topology and energy management (STEM): this protocol uses two different channels: the wake-up and the data channel, as represented in Figure 3.5. The wake-up channel is divided into fixed length periods to switch between sleeping or listening mode in order to detect incoming signals from others nodes. On the other hand, the data channel is always in sleep mode except if an external signal is detected by the wake-up channel. There are two different variants: STEM-B(Beacon) and STEM-T(Tone).

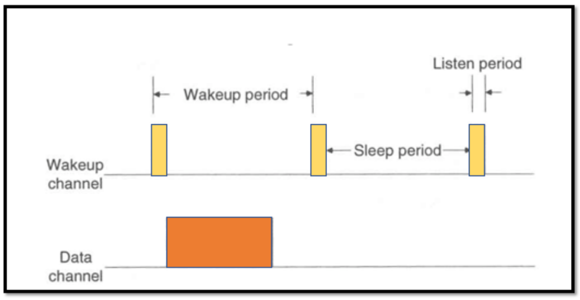


Figure 3.5: STEM duty cycle for a single mode [41]

In **STEM-B** each beacon indicates the MAC address of the transmitter and the receiver. On the communication process, the receiver picks up the beacon, and if it is the beacon it was waiting for, sends an acknowledgement frame back on the wakeup channel to inform that a signal was received and it can stop the beacon transmission. If the beacon is not received in the first attempts, the beacon will repeat the process at least for an awake period.

In **STEM-T**, the transmitter sends busy tones on the wake-up channel to all nodes on the network. This makes other nodes switch to their data channel. This way, the transmitter gets the attention from all receivers which will accept or not the packet and then go to sleep without any acknowledgement.

Comparing both variants, in STEM-B if several transmitters start to transmit at the same time it will lead to beacon collisions. In STEM-T the tone is transmitted for a maximum time even for the wake-up channels that aren't able to decode it. STEM-B shows to be more efficient to low data-rates while STEM-T is the better option to higher data transmissions.

Apart from the MAC protocol, to create a reliable communication link for packet transmission between nodes an error control mechanism is implemented. Two important modes of error control in communication networks are: the Forward Error Correction (FEC) and Automatic Repeat Request (ARQ). The most used mode in WSN is the FEC, which is a technique where errors are rectified with the help the redundant information. In ARQ technique the receiver provides feedback to the sender about the message received, sending a positive or negative feedback, leading to packet retransmission in the second case.

To summarize, two important aspects have to be taken into consideration in Data Link Layer: The MAC protocol that better fits the needs of the WSN application and the error control mechanism to implement in order to ensure reliability to the network.

Network Layer

The communication model is related to the network structure or topology [9]. An organized structure for a specific network brings several advantages in terms of energy consumption and scalability. For example, introducing hierarchies in the sensor nodes which make them coordinate some tasks. The topology network mostly implemented in WSN are Star, Cluster/Three and Mesh, which are presented in Figure 3.6. Depending on the final application, each one offers different advantages.

For example, **Star** topology is a simply and low power point-to-point communication where each sensor node connects directly to a sink node. **Mesh** topology is a multi-hopping communication architecture where each node connects to multiple nodes giving the advantage to provide a long range distance of transmission by routing traffic between nodes. Lastly, **Cluster/Tree** topology is a hybrid star-mesh architecture which takes the advantages of both topologies.

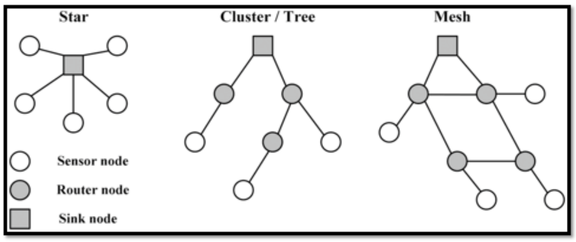


Figure 3.6: Network Topologies examples

Transport and Application Layer

The transport layer is responsible to route the acquired data from the sensor nodes or coordinator and send it to the upper levels, for example to internet, or to an external network [42]. Section 3.3 presents a benchmarking about several technologies used in transport layer.

The application layer, in the WSN's concept is responsible to deliver the information to the users [42]. In commercial applications for WSN's, this layer represents a platform where customers can monitor the data from the network in real-time.

3.3 Wireless Technologies for WSN's

The communication between nodes in WSN's is based on radio-frequency technologies [43]. These ones, are optimized to answer different needs, such as the data-rate, range and power consumption. Following, will be briefly presented emerging technologies that can be implemented in WSN applications. Some of them are more appropriate for WSN requirements than others, specially in terms of energy consumption. Any solution requires a study about the

WSN environment conditions, to conclude about the requisites in terms of price, consumption, security and range [4] [44].

Table 3.1 presents the results of a research about the emerging wireless technologies used in wireless sensor networks in the recent years [44]. These technologies can be divided into long and short range wireless communications. Firstly, are presented the ones which allows long ranges, higher than 1km, and then short range, which allow communications around 1 to 200 meters.

Technology	LoRa	SigFox	Cellular	BLE	Wi-Fi	Zigbee	Z-Wave	WirelessHART
Protocols	LoRaWAN	Sigfox	GSM/GPRS /4G/NB	4.2 /5.0	IEEE 802.11b/ g/c/ac	IEEE 802.15.4	Z-Wave	IEEE 802.15.4
Frequency	433/ 868 MHz	868MHz	900/1800/ 1900/2100 MHz	2.4GHz	2.4GHz/5GHz	2.4 GHZ 868MHz 915MHz	868.42 MHz	2.4GHz
Range	2-5 km (US) 15km (RS)	10 km(US) 30-50 km(RS)	35km (GPRS) 200Km (3G)	50-200m	50-100m	10-100m	30m	50m (Indoor) 100m (outdoor)
Data-rate	200bps - 100kbps	10 - 1000bps	35-170kps (GPRS), 120-384kbps (EDGE), 384kbps-2Mbps (UMTS), 600kbps-10Mbps (HSPA), 3-10Mbps (LTE)	1Mbps	150Mbps- 1Gbps	250kbps- (2.4GHz) 20kbps- (868MHz) 40kbps - (915Mhz)	250kbps	250 kbps
Consumption	Low	Low	High	Low	Medium	Low-Medium	Low	Medium
Costs	Medium	Medium	High	Low	Medium/High	Low	Low	Low

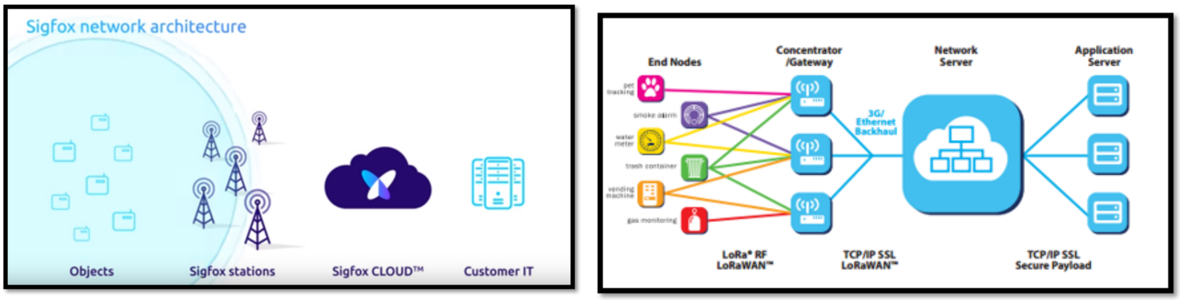
Table 3.1: IoT Wireless Technologies (The frequency bands presented on the table are referred to European Region regulations)

Sigfox and LoRa, are included in LPWAN, operating in Sub-GHz ISM bands [44]. They ensure different ranges depending if the network is deployed in an Rural Scenario (RS) or Urban Scenario (US).

SigFox[45] architecture is based on an ultra-narrow band communication system, which uses a small bandwidth, smaller than 1kHz. Figure 3.7a shows the Sigfox network topology, which consists in small messages up to 12 bytes transmitted between their own base-stations and the sensor nodes. It uses different modulations schemes for up/downlink, allowing downlink messages up to 8 bytes, using GFSK scheme on a 600Hz band, and 12 bytes to uplink using BPSK on 100Hz spectrum [44]. It uses three different channels to transmit the same message, which ensure quality in the reception point. The user can choose different engagement models based on the volume of devices and number of messages transmitted per day, since a basic packet with 1 or 2 messages per day, and no downlink messages, up to a platinum packet with more than 100 messages per day with 4 downlink messages. As shown in Figure 3.7a, Sigfox provides their own cloud service included, which the user has direct access to manage the data.

LoRaWAN [46] offers a chirp spread spectrum type modulation, allowing multiple data rates and spreading factors, which brings advantages and innovation in terms of connectivity and security for wireless communications. The architecture, as presented in Figure 3.7b is based on a star-of-stars topology. The gateways, also called concentrators or base-stations, are transparent bridges relaying messages between end-devices and a central network server in the back-end. Gateways are usually connected to Internet via by a 3G/4G, which route the packets to Network servers or application servers [44]. This technology supports payloads size from 19 to 250 bytes, to uplink and downlink communications, in compliance with the ISM regulations for Sub-GHz bands. The gateways can be public or private. The private ones, are operated by private individuals, usually by companies in industrial context. The public ones are managed by mobile network operators which are responsible for the network infrastructure, offering services to individual users. This service does not include a cloud or network server, as Sigfox.

Besides both technologies offer low power consumption and long ranges, the main reason why they are emerging and popular solutions in the markets, are the support given to the developers.



(a) Sigfox network architecture [45]

(b) LoRa network architecture [46]

Figure 3.7: LPWAN technologies

Cellular communications [47], as 2G/GPRS/3G and 4G allows long range communications and operate on licensed bands. Because of their high power consumption and cost, are not considerer the best solution for communication between the sensor nodes in wireless networks. However, these technologies offer high quality of service, and because of that, have been an option to use on the gateway to do the data routing to the cloud/application server. **GPRS** [48], also called 2.5G, is often used on the gateways in WSN's once it guarantees QoS and is useful as a gateway to send information for long distances. It shows to be very useful solution, if applied in zones that are not covered with 4G.

Recently 3GPP [47] approved a new technology, the specification of Narrow-Band - Internet of Things (NB-IoT) system to support low cost and power machine type devices through the narrow bandwidth up to 180kHz. This technology intends to be a non-expensive solution guaranteeing a high quality of service.

On the other hand, short range tecnologies very used in WSN's are following presented.

Zigbee [49] [50] is an open-standard wireless technology which respect the WSN requirements in terms of low cost, power consumption and data rate. The Zigbee technology is formed on the top of the IEEE 802.15.4, physical and MAC layer as shown in Figure 3.8. It has their own stack architecture, which include a security service provider with 128 bits AES encryption. It allows tree, star and mesh topologies, offering flexibility on network implementation. It operates in Sub-1GHz ISM bands, 868 MHz, or in 2.4GHz. The architecture network comprises two different device types: a full function devices (FFD) and reduced-function devices

(RFD). As the names indicate, FFD is more powerful than RFD and so it is used to coordinate a network or route data from it, while RFD suits simple applications such as the sensor nodes. For example, a mesh topology is used to reach higher ranges, once the date can be routed using RFD devices until the end-points. The power consumption of this technology depends on the topology used and the number of devices integrated. Mesh topologies, requires more power consumption because of the routing devices being wake more times to receive and send the data, on other hand, star topologies requires very low power consumption.

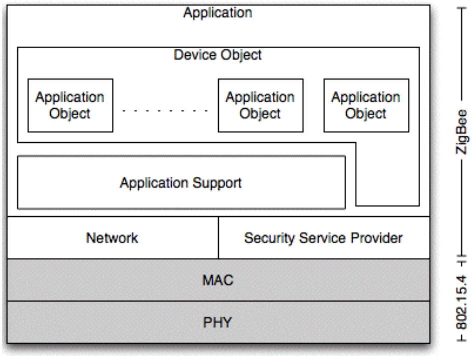
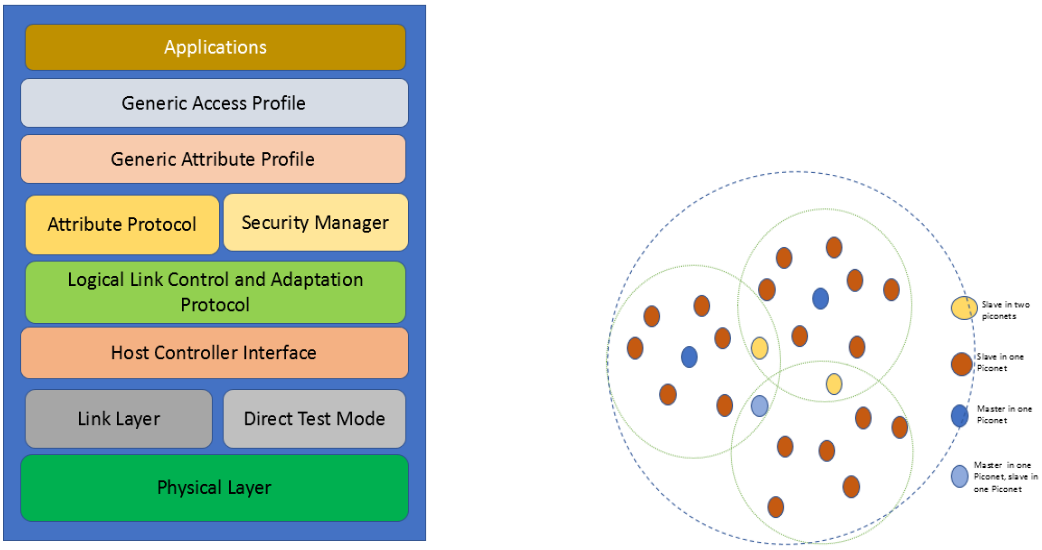


Figure 3.8: Zigbee protocol architecture [50]

Bluetooth Low Energy [51] [48] is a standard for short-range, low-power and low-cost wireless communication designed by Bluetooth Special Interest Group (SIG). It operates in a ISM band of 2.4GHz, and it is based on IEEE 802.15.1 protocol. Bluetooth last versions, 4.0 and later ones, offer more advantages in terms of power consumption and range compared with the classic Bluetooth technology. While first versions only allow three topologies, last versions provide mesh. Figure 3.9a presents the stack architecture, which is well defined, providing interoperability and support for the developer and application development. It comprises two different devices types: master or slave, which can create a network up to eight devices - seven slaves and one master - creating a basic cell named Piconet. The extension of basic cells is called Scatternet, as it is shown in Figure 3.9b. The Scatternet topology brings a big advantage in terms of scalability of the network. BLE provides a mesh topology, using a flooding method, where the data is send for all nodes in range. It provides many-to-many communications between devices, allowing higher ranges.

Wireless HART(Highway Addressable Remote Transducer) is an open wireless industrial sensor network protocol using the IEEE 802.15.4 standard. This protocol includes three main elements: Wireless Field Devices, Gateways and a Network Manager supporting a mesh or star topologies as shown in Figure 3.10 [52]. Topologies diversity allows greater versatility in the network configuration as higher ranges. This technology was specially designed for industrial applications, providing a fault tolerant routing protocol, to combat the electromagnetic interference which is common in industrial environments.

WiFi [53] is a technology based on IEEE 802.11 protocol, which is included in Local Area Network (LAN). Different versions of 802.11 have been launched by Institute of Electrical



(a) Bluetooth protocol architecture **(b)** A Scatternet configuration

Figure 3.9: Bluetooth stack and network structure [48]

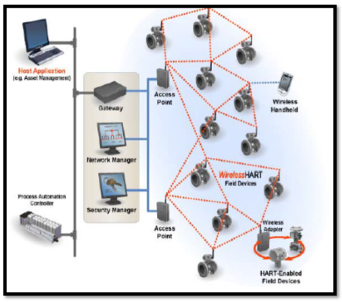


Figure 3.10: Network structure of Wireless HART [52]

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and Electronics Engineers (IEEE), with different security protocols, as WEP(Wireless Equivalence Protocol), WPA (WiFi Protected Access), or AES 128 bits encryption, and different modulation schemes, as Direct-Sequence Spread Spectrum (DSSS) or Orthogonal frequency-division multiplexing (OFDM), to improve the data-rate and range features. It operates in ISM bands and it is one of the most used technologies nowadays, once it provides wireless security connections for several devices. It allows high data-rates, from Mbps till 1 Gbps for the most recent protocol. In another hand, it requires high power consumption, which makes this technology not adequate for communications between sensor nodes. Once WiFi, is present in many places, especially in urban environments, it has gained high importance in WSNs applications, once it is possible to connect many devices directly to the Internet. Recently, a new technology, supported by Wifi Alliance, called WiFi HaLow is being developed in order to monetize the advantages of the WiFi and also provide low power consumptions.

6LowPAN is a technology based on IP connections between low power devices. IPV6 brought a huge address space, allowing to develop an open IP Standard, which allied to open messaging protocol based on IP, offer simplicity to the WSN development. Figure 3.11 represents a 6LowPAN architecture, which can be divided in simple, extended or ad-hoc networks topologies. There is a Edge router, which coordinate the network and route the data directly to the Internet or a Local server. This technology provides interoperability and is adaptable for packet formats. It can be applied over 802.15.4 protocols, providing a reduction on power consumption and congestion of the network, and network versatility.

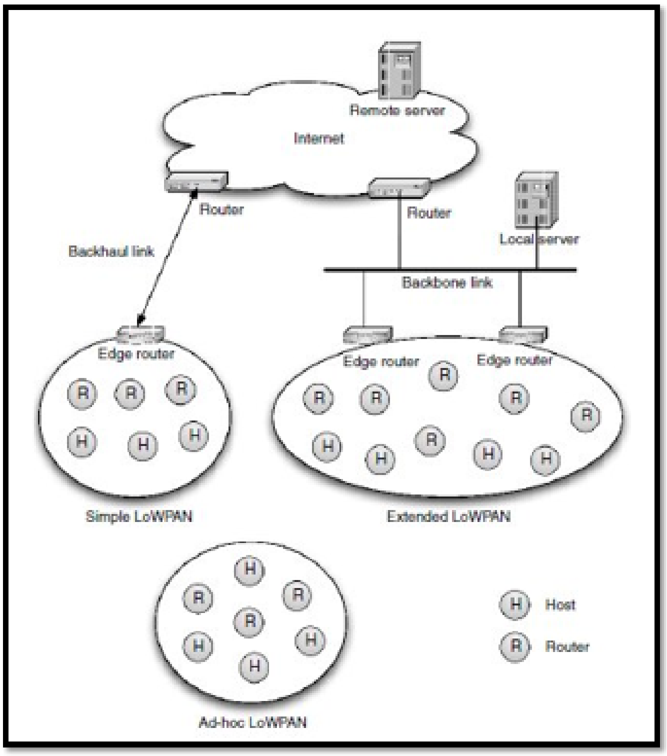

Figure 3.11: 6LowPAN architecture network [54]

Wireless technologies overview

It was presented some technologies which have been used in WSN's in the context of IoT. They differ in terms of topology, range, consumption, security, quality of service and price. Each one presents some features which make them more viable to apply on the context of *Salicornia* application. It is important to make reference to promising technologies, such as NB-IoT [55] and WiFi HaLow [56], which are not yet available on the market but promise to bring advantages in terms of power consumption, cost, and viability to the WSN's developments.

3.4 Sensor Node

As mentioned in Section 3.2.2, physical layer and consequently the hardware became a fundamental issue to take into consideration when developing a WSN.

Embedded systems are computer systems based on electronic elements. An example of an embedded system is a microcontroller. These systems are less expensive than computers and more low power consumption, which bring much more advantages when a high-performance system, as a computer, is not needed to process a simple program. Besides cost and consumption, they present advantages in terms of development flexibility, which is very important, to handle different needs.

A common node, if applied in WSN's context, have four main components, as shown in Figure 3.12 and are briefly explained below.

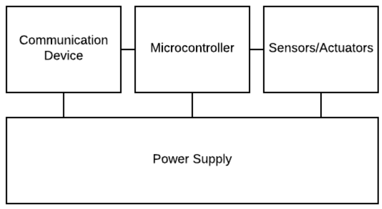

Figure 3.12: Main Sensor node hardware components

- **Microcontroller**: It is an embedded system, which process relevant data and executes code. It has included memory and peripherals. It can have different types of memory to store programs and data, as will be explained below. A few examples of peripherals are: watchdogs, PWM, timers, serial communication interfaces, counters, ADC and I/O ports.
- **Sensors and actuators**: are the devices that can measure or actuate on physical parameters of the environment, as explained in Section 2.3.
- **Communication device**: It is responsible for sending and receiving information over a wireless channel. If it is able to send and receive information over the same circuit it is called transceiver device.
- **Power Supply**: which can include batteries.

The aim of a wireless sensor network is to operate as efficient as possible in terms of energy consumption, once batteries require maintenance and are expensive.

3.4.1 Microcontroller

A microcontroller is the core of a wireless sensor node, which includes a processor, memory and peripherals. It collects data from the sensors, processes it and answer differently depending on the different events types. Since the explosion of sensor networks, a huge amount of microcontrollers have been designed to answer the needs of wireless networks. Because of the constant evolution, microcontrollers developers face new challenges in terms of keeping the same functionality and performance of the devices while simultaneously maximizing battery life[57].

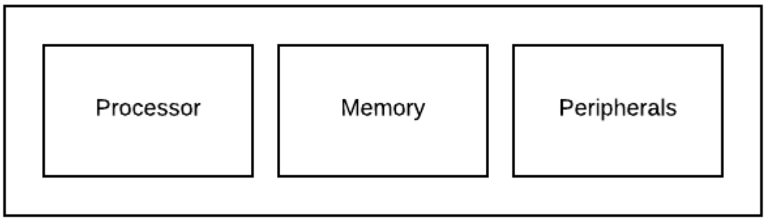

Figure 3.13: Microcontroller components

To select the microcontroller that better fits a specific application needs, some features must be considerer, such as:

- **Memory** Different memories are available as Random Access Memory (RAM), Read-Only Memory (ROM), Electrically Erasable Programmable Read-Only Memory (EEPROM) or Flash memory. Different applications requires different needs in terms of memory. While RAM is fast to store intermediate sensor readings, packets from other nodes and so on, its main disadvantage is that it loses its content if the power supply goes off. The program code can be stored in ROM, EEPROM or even in Flash Memory depending on how much of the code the application will produce. If RAM memory is not enough, Flash memory can serve as an intermediate storage of data but it will introduce a delay and requires more energy. To conclude, before purchasing any microcontroller a correctly dimensioning of memory sizes to optimize costs is important.

- **I/O Peripherals** A microcontroller can offer different peripherals, such as I/O digital pins, timers, ADC's, PWM generators, counters and watchdogs timers. Pins can be configured as input or output, which are usually grouped in ports. These pins can be analogue or digital. Analogue ports requires an ADC to convert it signal to digital. This conversion demands a voltage reference and comparators, which are included in microcontrollers, to perform the analogue measurements and convert them, called ADC. Timers, PWM and watchdogs are based on a pulsed created by the microcontroller clock, which can be configure by the developer.

- **Digital Interfaces** Universal asynchronous receiver/transmitter (UART), Inter-Integrated Circuit (I2C), and Serial Peripheral Interface (SPI) are examples of digital interfaces [58]. Digital interfaces are included in peripherals components of a microcontroller. These interfaces allow the communication between the microcontroller and external units, such as sensors or actuators. UART, is an asynchronous communication interface that allows serial communications between a Receiver (RX) and Transmitter (TX). On the other hand, SPI is a synchronous point-to-point and operates with a master-slave principle, allowing a multiple number of slaves using a Select Slave(SS) line, adding more four lines to synchronization and data transfer. I2C is another synchronous protocol but it only uses two single-ended wires to communicate, one for the clock and other to the data. It uses a byte address to identify which slave to communicate. These protocols are very used to integrate sensors with microcontrollers, and often available on microcontrollers boards.

3.4.2 Communication Device

Communications between device machines can be categorized into wired and wireless communications. For a long time, wired communications were the only option to communicate over long distances, as for example, the Telephone. After wireless/radio revolution, wired communications become undesirable or even inappropriate to deploy in some environments, such as hard reach places, or if it is required a high number of nodes spread around a large area.

For these reasons, new solutions appeared such as, like radio frequencies, optical communications, ultrasound and magnetic inductance. However, communications based on Radio-Frequency (RF), are the ones that best answer the needs of a WSN once it provides long ranges and high data rates, with reasonable energy consumption.

Wireless technology consists in modulate the electromagnetic energy waves using amplitude, frequency or phase techniques modulations to transmit data. By using an antenna and applying modulation techniques, it is possible to convert an electrical signal into radio waves. The receiver, must be able to demodulate the input into an electrical signal again. Figure 3.14 present the general and basic principals of a radio transmission and reception data, figuring an example of audio data, and because of that is used a microphone to convert sound into electrical waves. The amplifier, is used when a weak signal requires amplification. The function of the oscillator is to rise a carrier wave till the amplified signal, in order to both signals be add. After this, the modulator output is a radio wave. In the receiver, it has a demodulator, responsible to extract the original signal by a demodulation process.

Nowadays, transceivers are often used for communication devices, once they can receive and send information, incorporating modulation/demodulation types, amplifiers, filters and mixers.

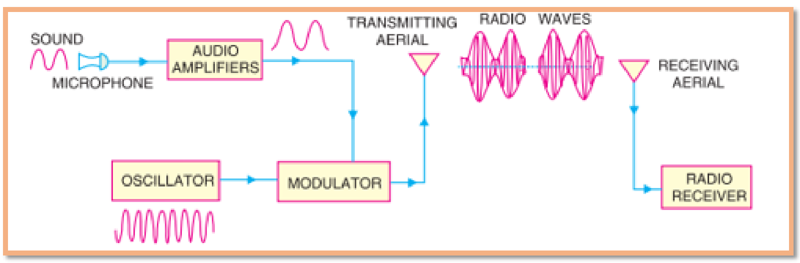

Figure 3.14: General principles of radio broadcasting [59]

To select an appropriate transceiver, some issues need to be raised such as: if they have different carrier frequencies to alleviate congestions problems, if they can operate in different power mode states to save energy, also if they allow distinct data rates and modulations. Other main features to take into consideration are the capability of controlling the power transmission, the receiver sensitivity and frequency.

In terms of a microcontroller energy consumption, memory and radio transceivers afford different configuration which allow developers to save a great amount of energy.

3.4.3 System on Chip

To conclude about the sensor node, which requires different hardware components, it will be briefly described SoC, another solution to the sensor node. Figure 3.15 shows an example of the basic model of it architecture. These devices are known as an integrated solution that brings many advantages for the product development. The SoC components are connected by an one-chip communication architecture which support data communication between inter-components and external devices. With the SoC evolution their complexity increased, in order answer the increasing performance needs for nowadays applications [60].

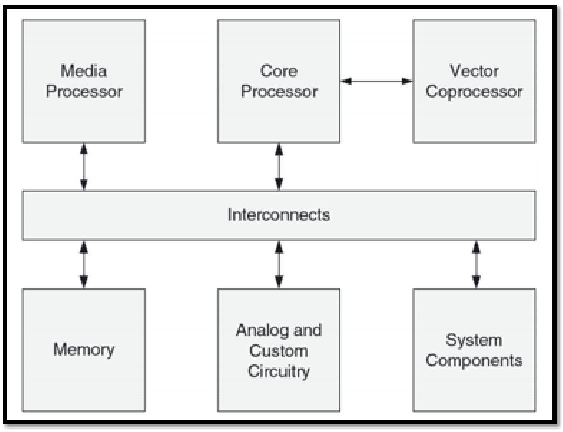

Figure 3.15: Example of a system-on-chip model [60]

The SoC appeared on the market with a great value for money, and because of that they have been used to develop sensor nodes, which integrates a communication module. Table 3.2 presents a research about SoC's available on the market, which offer a processor, memories and transceiver integrated. It provides simplicity once it allows the sensors integration, programming sleep/active and transmitting/receiving modes. Their price vary in terms of performance, specially in terms of the CPU and memory integrated.

In Table 3.2 are presented four different system on chip devices. The main difference between them is the Central Processing Unit (CPU) performance, the clock, and memory. A SoC is designed to be as low power consumption as possible, but powerful processors consume more energy than a simple 8-bit processor. Companies, such as Atmel, Nordic and TI focused in developing dedicated solutions for certain technologies, such as Bluetooth, Zigbee, WiFi or for communications in ISM bands. It comes with dedicated features that best answer the technology requirements, allowing a higher performance for a lower price. Another important

SoC	Espressif ESP8266	Atmel ATWINC1500	Nordic nRF52832	TI CC1110
CPU	32 bit, 80 MHz	32 bit, 10-40 MHz	32-bit, 64MHz	8-bit, 26Mhz
RAM	50 kB	160kB	64kB	1,2,4 kB
ROM	N/A	128kB	N/A	8,12,32kB
Flash	Add by SPI	4kB	512kB	8,16,32Kb
Consumption	15 mA	N/A	N/A	5m A
Technologies	WiFi	WiFi, Bluetooth	Bluetooth, SubGHz Bands	SubGHz bands
Transceiver Consumption (Tx /Rx/Sleep)	120 ∼170 mA 50 ∼56 mA 20 uA	224 mA 52mA 380 uA	3∼16mA 5-12mA 400nA	33.5 mA 20.5mA 0.5uA
Price €	2 - 15	10 - 30	7-25	2.6 - 6

Table 3.2: Several SoC solutions available on the market

point to take into consideration, is the support that companies provides to the users, in terms of datasheets or design notes, which facilitates the development process and save time over the project.

3.5 Chapter Considerations

The aim of this chapter is to present the main engineering topics that a developer need to be familiarize in order to produce an efficient wireless sensor network to monitor *Salicornia* plantations. The last years have brought innovation for WSN's, and because of that, different architecture layers have been proposed and used in the more diverse applications. This chapter presents a simple architecture, based on the know OSI model. Wireless technologies offer several options to the developer. More options mean more possibilities to be perfectly content–right, and so, knowing each one, it is easier to find an efficient solution to apply on *Salicornia* context. To conclude, the hardware is the turning point of the solution, once it is responsible for the system performance. Because of that, it is described the main features that must be taken into consideration before selecting the final hardware tool.

4

Proposed Architecture

4.1 Introduction

This chapter describes the proposed architecture as well as the mechanisms and protocols to achieve the final purpose of this dissertation.

Section 4.2 describes the environment to be covered by the WSN.

Section 4.3 presents the proposed architecture, MAC and communication protocol between sensor and sink nodes. To conclude, some wireless technologies are analyzed in order to evaluate its adequacy for this project.

4.2 WSN Environment

As mentioned in Chapter 2.2, a WSN application depends on several factors, and one of them is the environment where it will be deployed. Figure 4.1 shows the lagoon area where the *Salicornia* plantation need to be monitored. Near Aveiro down-town area and a highway, this area is divided in small areas to efficiently monitor all plantation. In Section 2.2.1 the project requirements were already defined.

Although localized near the city center, this area is considered wild because is not in reach of an electric distribution grid and the access is difficult and without any security. Because of that, wireless solutions are the ones that best answer the needs of *Salicornia* plantation.

As mentioned in Chapter 2, the main requirements to deploy a wireless sensor network are: a very low power consumption, easy of implementation and low cost. Low power, because batteries maintenance in a lagoon environment is expensive. It must to be easy to deploy, to facilitate the deployment network and nodes replacement. Once it is considered a wild area, where everyone can have access, it is susceptible to robbery or damage, and because of that the price must be as lower as possible.

This lagoon have different characteristics depending on the season. In winter time, it can be completely waterlogged. In spring and summer seasons, the lagoon can have small areas

Figure 4.1: Area and location of *Salicornia* plantation in Ria de Aveiro

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with puddles of water or can have completely dry areas. For this reason, it is necessary to divide the total area into smaller ones to efficiently monitor them.

A water tank is the only construction that exists nearby the plantation, used to irrigation in the summer period. In order to reduce the cost of the project, it is important to use existing resources. The tank is a good option to install the sink node, since it is a higher point and with a sturdy structure. However, for the sensor nodes, it is necessary to use stakes that support and ensure the stability of the node sensor.

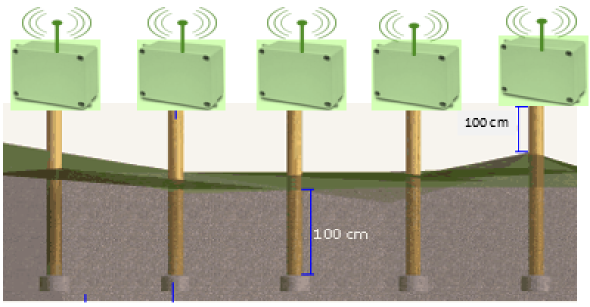


Figure 4.2: Proposed structure to project the hardware in *Salicornia* plantation

In Figure 4.2 is presented a solution to deploy an eco-friendly, wooden stakes, and resistance structure to support the sensor nodes. It is also need to use waterproof boxes to protect the hardware of the sensor and sink node against corrosion. The box should be at least one meter above the ground so that the hardware is not destroyed in case of flooding and at the same time allows better performance in the reception and transmission of data in line of sight.

Although to be considerer a wild area, causing difficulties in deploying a WSN, it is near the down-town area, around 200 m of distance.

4.3 Global Architecture

Figure 4.3 presents the network architecture proposed to monitor the *Salicornia* plantation. The sensor nodes are spread along the lagoon area and data is periodically collected, as the user/client decides. The network is organized in a star topology, where each Sensor Node communicates to the Sink Node. The Sink node is connected by a serial bus to a computer which will store, process and provide the collected data to the user.

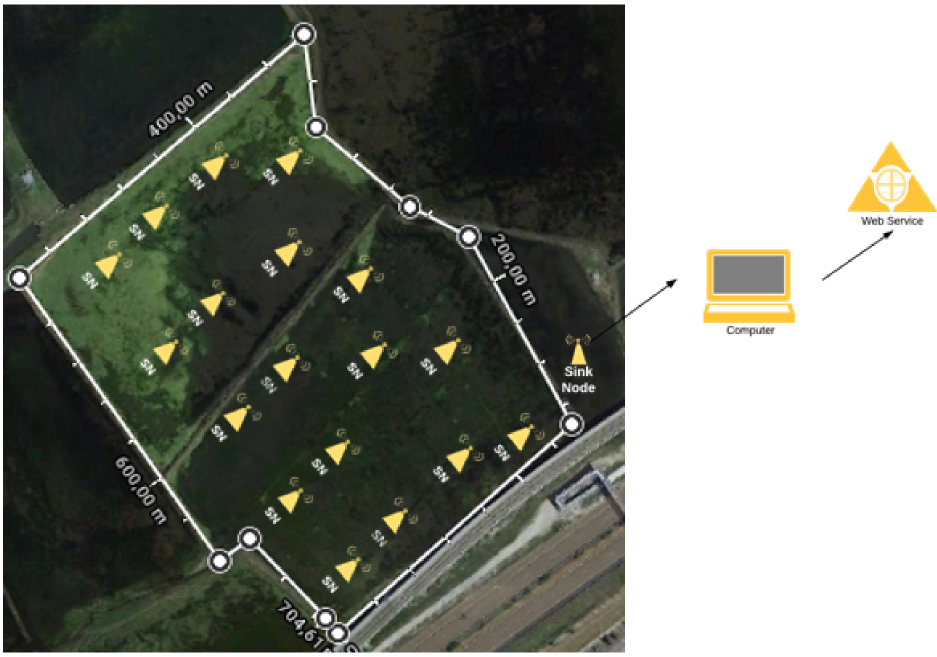


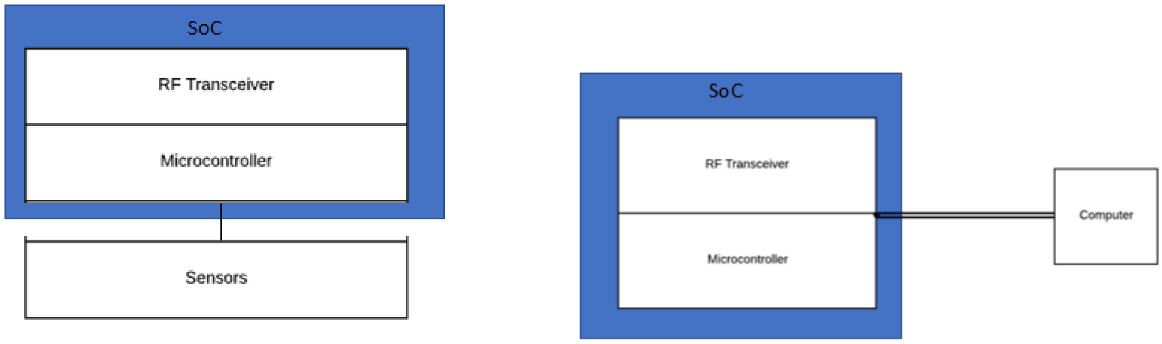
Figure 4.3: Architecture of WSN to monitoring *Salicornia* plantation

4.3.1 Sensor and Sink Node hardware

For the development of the Sink and Sensor nodes, is proposed to use CC1110 SoC's from TI, once they offer the necessary performance at low cost.

The sink node requires more performance than the sensor node, and consequently, its energy consumption is higher. However, a SoC offers features that respond to both, the very low power consumption needs of the sensor node as well as the higher performance required by the sink node.

In Section 3.4.3 it was presented the main advantages of using SoC in wireless sensor networks. Depending on the selected wireless technology, such as Sigfox, LoRa or other RF solutions, their transceivers are easily integrated into the microcontroller or Soc's. Given the versatility and adaptability to different scenarios, it is proposed to use a SoC devices for the development of the project, as shown in Figure 4.4.



(a) Sensor Node Hardware Architecture

(b) Sink Node Hardware Architecture

Figure 4.4: SoC devices used to program the Sink and Sensor nodes

4.3.2 Sensors Integration and data acquisition

The sensor node process the sensors firmware. Figure 4.5 shows the data acquisition from sensors divided by layers. Depending on the sensor and their features, it can be digital or analog. In Chapter 2.3, are presented the main features that are required to process sensor integration. In Sensors Controller layer, the device drivers for each sensor is deployed and processed, and then data is saved in a buffer to be then sent.

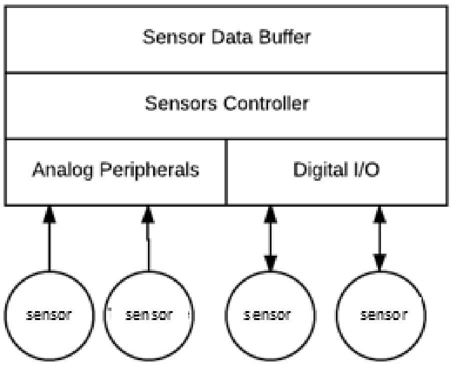


Figure 4.5: Abstract layers for data acquisition process

4.3.3 Communication between Sink and Sensor nodes

It is proposed to use wireless communications using 433 MHz ISM band, between sensor and sink nodes, as shown in Figure 4.6.

It is expected that the lagoon area offers line of sight and lower or even null interference from other RF-devices. The [433,05 - 434,79]MHz band, as explained in Section 3.2.2, is an unlicensed ISM frequency band. Despite the limitations of ISM band, monitoring a *Salicornia* plantation requires very low data transmission per day, which does not represent a problem

Figure 4.6: Network architecture with SoC devices with 433MHz band transceivers

for this application. This solution presents two main advantages: 433MHz band offers a reliable transmission distance up to 500m [38] and it has higher immunity against to signal obstructions, reflections and multipath fading. Given the lagoon area, it is expected that this solution cover all plantation with communication point-to-point between a sensor node and the sink node.

Topology

In terms of the topology network, a star structure is proposed, as shown in Figure 4.7. A star topology offers two main advantages: deployment simplicity and low power consumptions.

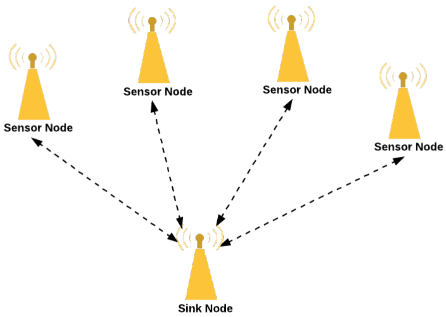


Figure 4.7: Star topology communication network

The communication between Sink and Sensor node consists on data and acknowledge messages. In order to avoid collisions between nodes, which result in additional energy consumption, a MAC protocol is also proposed to monitor *Salicornia* plantation, is presented in the next section.

MAC Protocol

In Section 3.2.2 different MAC protocols was described to evaluate which is the one that best correspond to *Salicornia* application. The proposed MAC protocol operates asynchronously, given the low amount of data per day that need to be transmitted, the costs of development and deployment must be reduced.

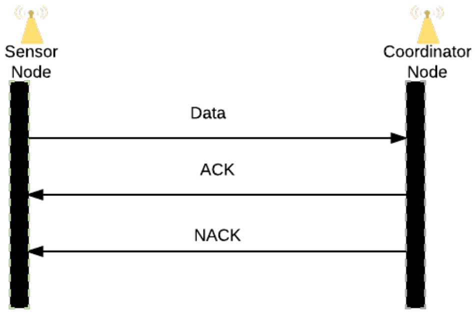
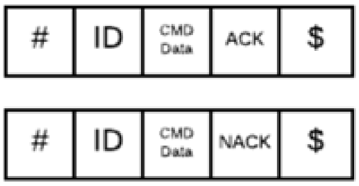


Figure 4.8: Messages between Coordinator and Sensor node

Figure 4.8 shows how messages control between the network. They are based on Data, NACK or ACK messages between the sensor nodes and the sink node.

(a) Packet format to Data Transmission



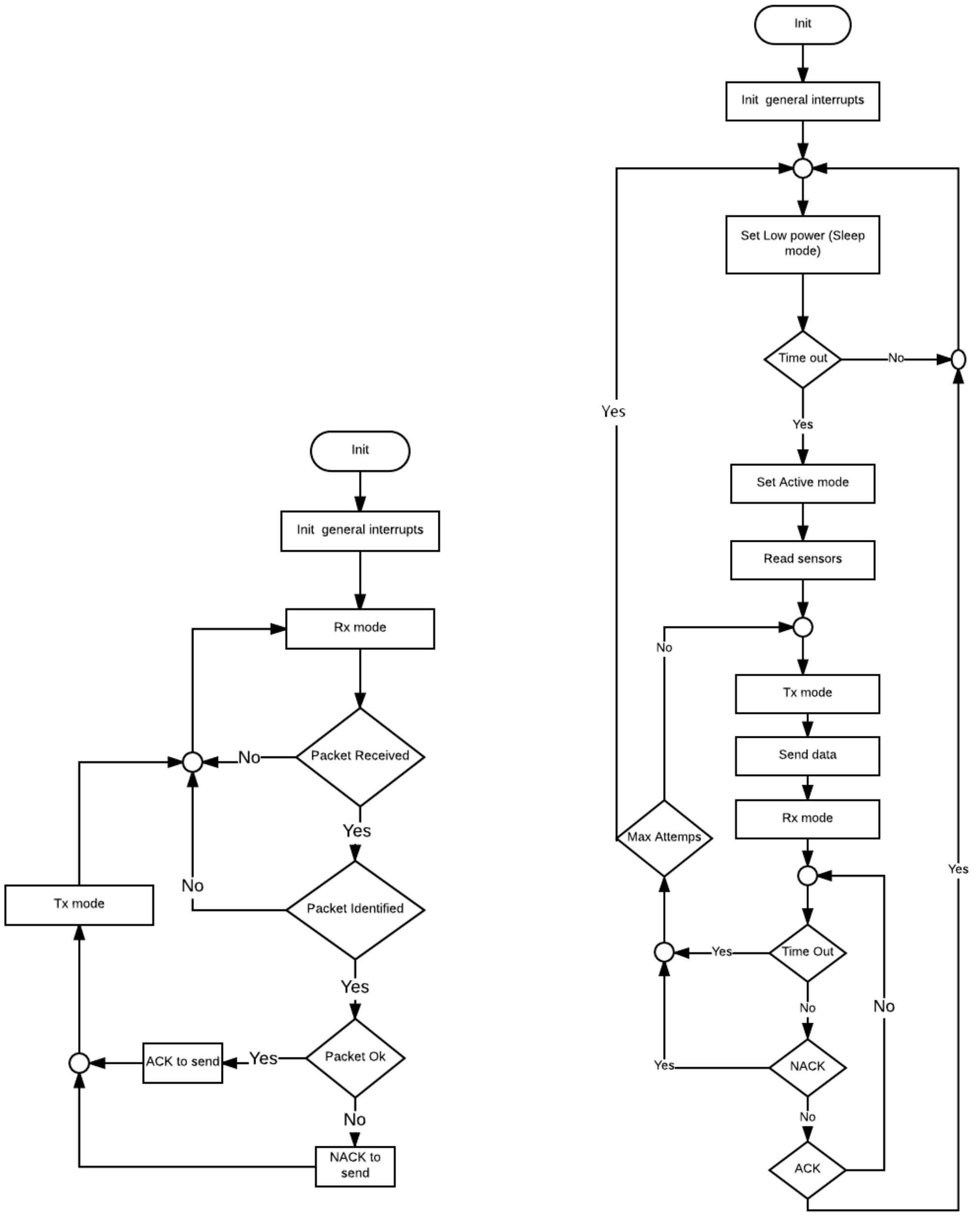
(b) Packet format to ACK and NACK

Figure 4.9: Proposed structure for data packets

Figure 4.9 presents the packet structure proposed for each message. The structure presented intends to enrich the robustness of the protocol through the implementation of a Checksum byte, Sequential number, payload and ID, facilitating the interpretation of the received packet, excluding external packets to the network and detecting packet losses.

The packet structure must include an ID byte indicating which sensor node is communicating in order to understand which area is being monitored. The Comand Data(CMD data) byte allows to process which type of packet is received: Data, ACK or NACK, making code implementation easier.

The flow chart with the processes in Sensor and Sink nodes is presented in Figure 4.10. In the sensor node, Figure 4.10b, after the initial system setup, the system is set to remain in Sleep Mode in the maximum power saving mode. When the time expires, exit Sleep Mode



(a) Flow chart of Sink Node messages **(b)** Flow chart of Sensor Node messages

Figure 4.10: Sink and Sensor node flow char

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and immediately reads the sensors and send a DATA packet. After sending the data, the same node sensor waits for a feedback message. This feedback can be from a packet which was sent and received successfully, or, in a second hypothesis, the packet was not delivered or has been deteriorated. Afterwards, the Sensor node goes back to sleep mode. If the Sensor node, which is waiting for a period of time, did not receive an Acknowledge (ACK), it will retry the packet transmission a given number of attempts. If after all attempts done, it does not receive an ACK, the sensor node gives up of that packet and goes to sleep mode.

In other hand, the Sink node, Figure 4.10a, processes the packets received from the different sensor nodes, and send an ACK or NACK as the packet was successfully received or not. This way, the sensor node will receive that information and repeat the packet transmission. As mentioned before, the sink node is more power consumption. In this proposed MAC protocol, the sink nodes never enter in sleep mode, it is always listening and waiting for a packet. Next, it is proposed some options how data from the sink node can communicate remotely to the computer or even directly to a web service.

4.3.4 Communication between Sink Node and User/Client(Gateway)

The communication protocol between the sink node and user is obtained by serial communication protocol, UART, between the sink node and a computer. This method is only efficient to test the deployed WSN, however, is not a plausible solution for a final application. It is important to clarify that this solution is merely used to test the sensor network.

As mentioned before, this network requires a very low bandwidth to successfully make the communication between the Sink and the Sensor nodes. Likewise, communication between the sink node and a remote computer or web service does not require high bandwidth, less than 1kbps.

Solutions such as cellular(GPRS), Sigfox and LoRa, are analyzed. They can be integrated into the Sink mode, in order to operate as a gateway, allowing the communication of data to a computer/server remotely. The different proposed solutions, described before in Chapter 3.3, are analyzed according to the specifications of the environment and application requirements represented in Chapter 2.2.1.

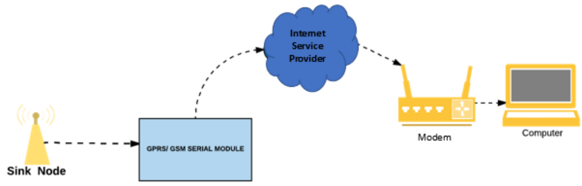
Cellular

As mentioned in Chapter 3.3, cellular communications are the most expensive and power consumption technologies. However, they guarantee Quality of Service (QoS), and network coverage along the lagoon area, as shown in Figure 4.11b.

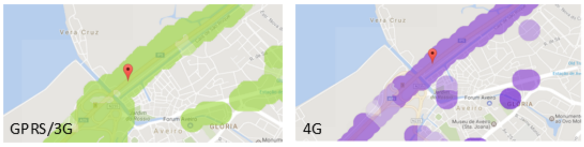
Figure 4.11a presents a solution with GPRS technology. A GPRS module, which is connected to the sink node provides communication data-rates up to 170kbps, much more than the required. However, a common GPRS module, consumes around 400 mA to transmit or receive data, is expensive and require a monthly payment. After all, the computer need to be connected to a modem, which is a modulator/demodulator able to decode/encode GPRS signals.

LoRa

A mentioned in Chapter 3.3, LoRa was designed and developed to answer the WSN needs, and because of that diverse transceivers, SoC's and applications have appeared in the marker.



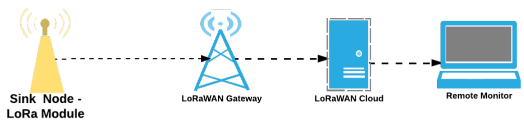
(a) GPRS technology as a gateway solution



(b) Cellular technologies coverage in Ria de Aveiro [61]

Figure 4.11: Solution with GPRS technology

Figure 4.12a presents a possible solution using a LoRa transceiver directly connected to the SoC. LoRa network requires their own gateways. The user/client can buy or build their own gateway, using it specially to monitor the *Salicornia* plantation, which need to be connected to Ethernet or WiFi. In other hand, there are already LoRa Gateways services, where data is redirected to web services applications, such as The Things Network [62]. Near the city center, there is a LoRa gateway, which can be possible used to test a solution in the *Salicornia* plantation environment, as shown in Figure 4.12b.



(a) LoRa technology as a gateway solution

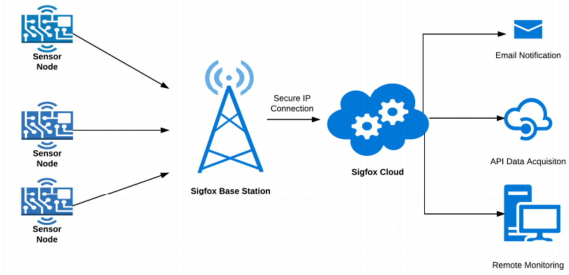
(b) coverage in Ria de Aveiro [62]

Figure 4.12: Solution with LoRa technology

Sigfox

Sigfox transceivers are low power and can be connected to a microcontroller or SoC, which communicate directly to their own base stations and their own web services, where data is directly available to the user. The different solutions it offer to the user, as email service, API's, or remote monitoring, as shown in Figure 4.13a, brings several advantages in terms of saving development and deployment time, which increase the value of this service. However, the main disadvantages of this technology are the limitation of bytes per uplink/downlink message and the price per message. Once *Salicornia* plantation requires a few messages per day, it can be a good choice in terms of price and QoS.

In terms of coverage, as shown in Figure 4.13b, tests were performed in Aveiro [63], which shows signal robustness in urban environments.



(a) Sigfox technology as a gateway solution

(b) Tests coverage Sigfox performed in Aveiro [63]

Figure 4.13: Solution with Sigfox technology

As a conclusion of the wireless technologies that can be used as gateway between the Sink node and the remote computer, GPRS technology is the one that least fits in the context of the application, once it is more power consumption and expensive. Newer technologies such as Sigfox and LoRa offer more services and implementation support, which results into cost savings and increased network efficiency and longevity.

The final technology to integrate in the *Salicornia* plantation as a Gateway to upload data for a remotely computer or web service, need to be a decision of the client/user, once all technologies have a price associated.

5

Implementation

5.1 Introduction

This chapter describes in detail all the implementation done along this dissertation, based on the proposed architecture presented in Chapter 4.

In Section 5.1 is characterized the hardware used to implement the wireless sensor network. In addition, it also presents the sensors used and their characteristics and operating mode.

In Section 5.2 is presented the MAC and communication protocol implemented.

In Section 5.3 is described the data acquisition implementation and how to process the data.

5.2 Hardware and Software

The development of this project depended on the tools available in the laboratory, as the SoC, as well as the sensors. As mentioned in Chapter 2, it was part of the objectives to integrate salinity, temperature, humidity and soil moisture sensors. However, the first impasse, was the lack of availability of a salinity sensor, which was being developed by a colleague working also in a *Salicornia* project [63]. Since the development of the project was delayed, it was not possible to integrate the sensor in time in this project.

In the same way, the selection of humidity and temperature sensors was the only option available in useful time, in the laboratory, was DHT11 sensors.

The SoC available are modules CC1110 Sub-1GHz from Texas Instruments. The Integrated Development Environment (IDE) used along the project was the IAR EMBEDDED WORKBENCH, which supports the tools required to program the CC1110. The code was written using the C language.

TI provide the *SmartRF Studio* [64], which is an application that allows to test the behaviour of different modulations, data-rates and frequency bands, only using their modules. It was used to test the behaviour of different modulations schemes.

(a) CC1110 SoC **(b)** CC1110 SoC with evaluation module

Figure 5.1: CC1110 Modules

5.2.1 CC1110 Modules

The CC1110 [6] modules from TI are low power sub 1GHz SoC devices, which are designed for low power wireless communications. The biggest advantages of these modules are the high performance of the RF transceiver, small package size, cost and availability of several advanced low-power operation modes.

The main specifications of CC1110 are presented in Table 5.2 and are divided in modules: Radio, Low-power and MCU. Figure 5.1a presents the device modules, with an antenna of an eighth wavelength monopole [6].

CC1110	
Radio	RF Transceiver Programmable output power High sensitivity(-120dBm) 315/433/868/915MHz
Low Power	Low Current consumption Three different power modes
MCU, Memory and Peripherals	8051 microcontroller core @26MHz Direct Memory Access (DMA) functionality 32KB Flash 4KB RAM Advanced Encryption Standard (AES) UART/SPI/ADC/

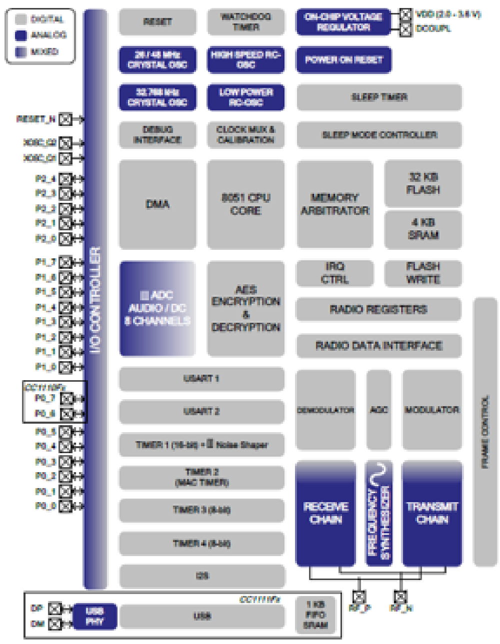


Figure 5.2: CC1110 main features [6]

Radio module

The radio module allows to configure different frequencies, modulations, data-rates and output power. Figure 5.3 shows the packet format, which supports a fixed or variable packet length up to 255 bytes. The format is configurable, but a Preamble bits and Sync Word are mandatory, which are automatically processed, added and removed by the radio module.

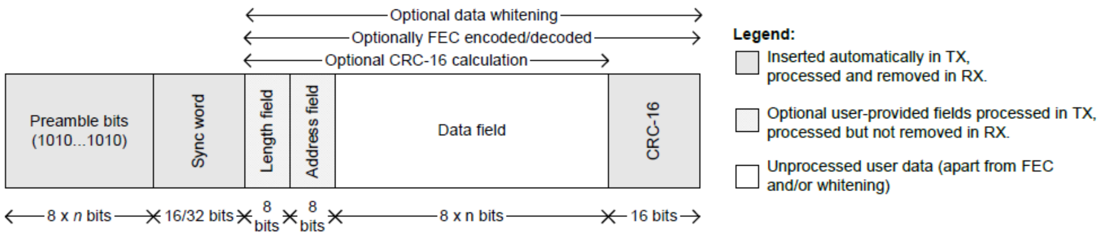


Figure 5.3: CC1110 Packet format [6]

- **Preamble bits** is an alternating sequence of zeros and ones, which is set by the modulator and sent to initiate a transmission;
- **Sync Word** is a two byte value set by CC1110 registers. These bytes provide the synchronization of the incoming packet.

It offers the different modulation formats, which are based in distinct frequencies and phase-shifts. It offers different modulation: FSK, Minimum-Shift Keying (MSK), ASK and GFSK, which are easily configured by internal registers. The different modulations performance can be tested with SmartRFStudio, an IDE provided by TI.

Low Power module

This SoC provides four different Power Mode (PM), which are presented in Table 5.1. The system clock can be set to 26MHz or to 12MHz with a crystal oscillator. The lowest clock is archived using a low power RC oscillator, which provides 32.768kHz.

To implement the sleep mode, it was used the power mode 2, operating at 32.768kHz oscillator. Not only because it offers an efficient power consumption performance but also do not require external signals to wake up from that mode.

The lower the frequency band, the lower the power consumption required by the module. A higher output power, higher is the range, and consequently, higher is the power consumption. The output power is set to 10 dBm which provides higher ranges in distance.

The current consumptions presented in Table 5.1 correspond radio consume if selected 433MHz. The table is based on reference tables provided by TI.

Mode	Consumption	Conditions
TX	33.5mA	10dBm output power & Clock@26MHz
RX	20.5mA	250kBaud & Clock@26MHz
PM0	4.3mA	Same as active mode
PM1	220uA	Clock@32.768kHz oscillator
PM2	0.5uA	Voltage regulator off
PM3	0.3uA	Voltage regulator and oscillators off

Table 5.1: Operating modes consumption in CC1110 [6] at 433MHz

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The Friis Equation 5.1 [65], for a line of sight, allows determining the range propagation of an antenna, knowing the output power of RX and TX and their antennas gain.

$$P_r = P_t + G_t + G_r + 20log(\frac{\lambda}{4\pi}) - 20log(d) \tag{5.1}$$

Based on TI notes and provided antenna[66], the maximum range propagation in line of sight, d, is 2km [65].

MCU, Memory and Peripherals

This SoC provides a 8051 MCU, which is 8-bit processor. In terms of memory, it include 32kB non-volatile flash memory and 4kB of internal SRAM.

It offer several peripherals features, such as a DMA controller, eight ADC's, a watchdog timer, five timers of 16 and 8 bits, two UART or SPI ports, 21 pins configurable for I/O. Another features, such as, a I2S interface, USB controller and a 128-bit AES coprocessor are also included.

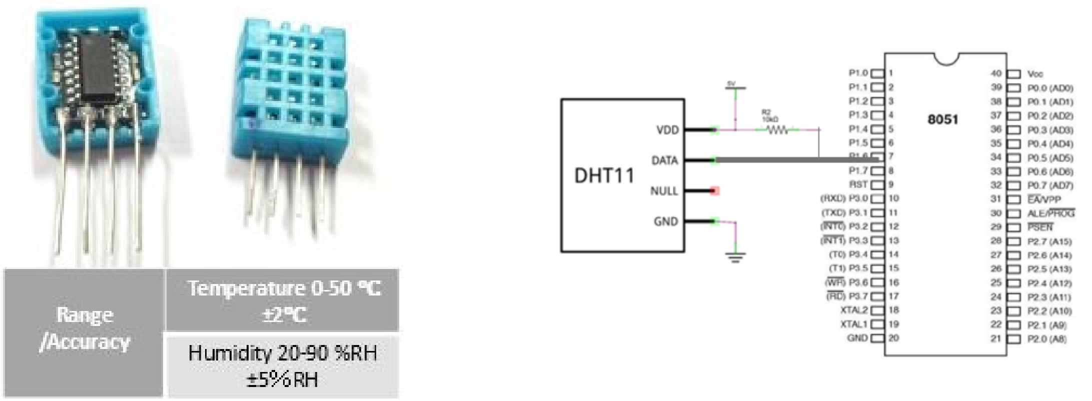
5.2.2 Sensors

Section 2.3 presented the different sensors needed to monitor the *Salicornia* plantation. As noted at the beginning of this chapter, due to the lack of available material, only a temperature and humidity sensor was present in useful time to be integrated. This way, the available sensor is a digital sensor DHT11.

DHT11 [67] is a digital sensor that reads humidity and temperature. This sensor uses a single-bus communication pin (DATA), which is synchronously connected to I/O microcontroller port, as shown in Figure 5.4b. It has also a ground and power pin.

Figure 5.5 presents a flow chart which briefly explains the data reading process, which is based on a master-slave communication protocol. The device driver implemented to read the data from the sensor was based on the presented flow chart.

The microcontroller, as a master, sends a wake-up signal to the sensor. This wake signal is based on a high signal detection. If the sensor is properly connected to the data pin, it will identify the signal as a request from the master. This way, it will answer with a pulse and prepare a buffer of 40 bits to send to the master. The slave sends impulses separated by time slots. Bits are detected as 1/0 depending on the high output signal period. In order to detect



(a) DHT11 **(b)** DHT11 integration with a microcontroller

Figure 5.4: DHT11 features [67]

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the data message, it is set a timer to interpret the received bits. If an error is detected, like any external signal detected, the reading process starts again.

If no error occurred, the timers will read 40 bits and separate then into a DATA buffer, which is then divided in 5 bytes: a temperature, null,humidity, null and a CRC byte. If the CRC bytes does not correspond to the sum of the temperature and humidity bytes, it means that an error occurs during the transmission. This way, all process is repeated.

5.3 Communication Protocol

The communication between the nodes must be configured in a way that minimizes the power consumption and still efficiently answers the network needs. The next section presents a proposed network structure which allows several modules to communicate with the sink node avoiding collisions and idle time listening.

This section aims to explain, in detail, the implemented Packet Structure, the MAC protocol and the implemented code to perform the network. To conclude, it is presented the used method to process the data from sensors in the sink node.

5.3.1 Packet Structure

In Section 4.3.3 is presented the proposed Packet Structure for the different messages passing between the Sink Node and Sensor Nodes. The structure of the packet, in addition to transmit the sensors data, also serves as a test to verify the reliability and behavior of the network. It is included to the packet a sequence number, attemps and checksum, which allows to calculate the network packet loss. There are three types of messages: Data, ACK, and NACK. Following will be described each one.

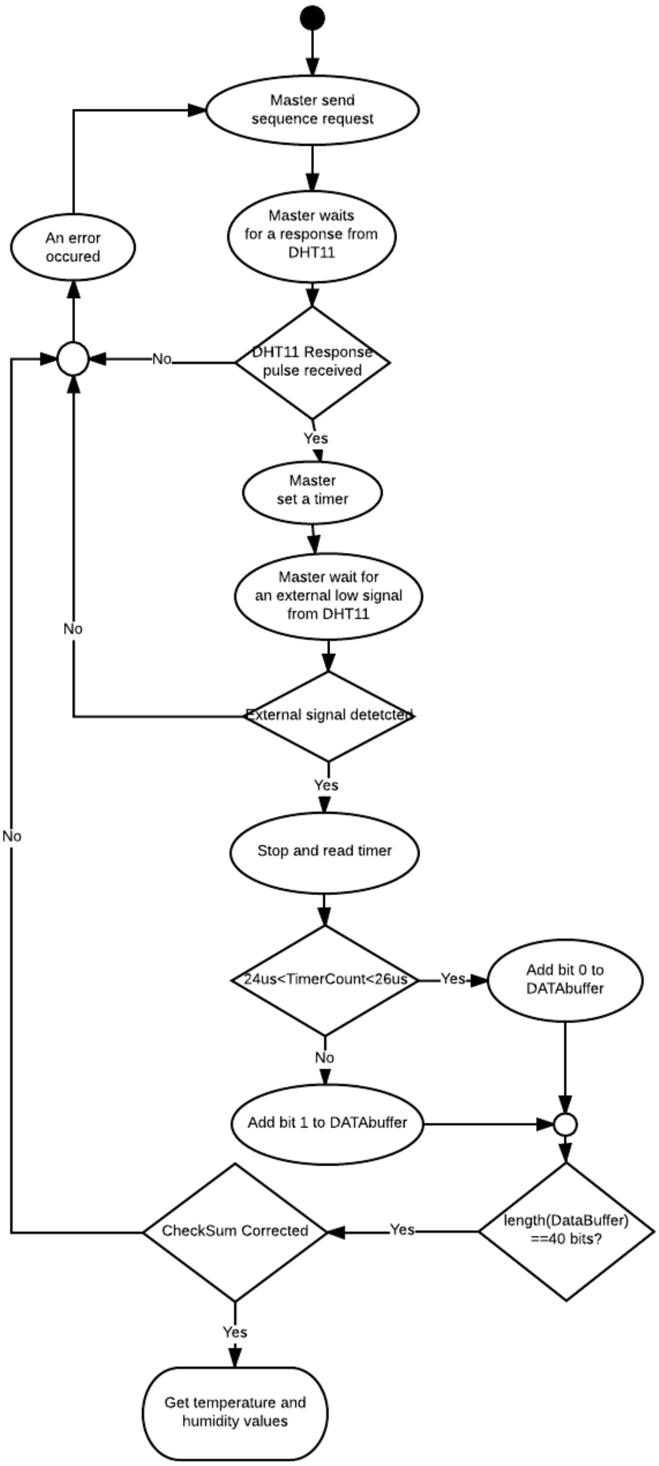


Figure 5.5: Operating principle of DHT11

Data Message is transmitted from the Sensor Node to Sink Node. In Figure 4.9 is presented the packet divided by bytes, which starts and ends with an identifier.

- **ID** identify the Sensor Node that is transmitting;
- **Command Data** Divided into three options, inform which is the type of message: DATA, ACK or NACK;
- **N Payload** Indicates the total number of bytes that is expected to receive;
- **Attemps** Informs the number of times that a Sensor Node tried to retransmit the same packet;
- **Sequence Number** Informs which is the packet being transmitted to know if packets were lost. Every 255 packets sent, it is reset and restart from zero;
- **Payload** Sensors data is divided by bytes and sent by order. Include bytes from temperature and humidity sensor;
- **CheckSum** This byte is the sum of all bytes of the packet. It is useful to check if the packet was deteriorated. Allows to conclude if is necessary to retransmit a packet. This means that this byte determines if a NACK or ACK will be sent.

ACK and NACK present a simple structure, with a start and end identifier.

- **ID** identify the Sensor Node, which has to receive the positive or negative feedback message. It guarantees that a sensor node does not receive an ACK from other Sensor Node, by mistake.
- **Command Data** informs which is the type of message that is received. It is useful to differentiate from possible interference from another Sensor Node.
- If the packet was successfully received, the fourth byte is filled with a 1, an ACK, otherwise is filled with a 0, which indicates a NACK message.

The final Packet Structure implemented is shown in Figure 5.6. Therefore, a total of 20 bytes are needed to a Data message and 9 bytes to ACK/NACK messages.

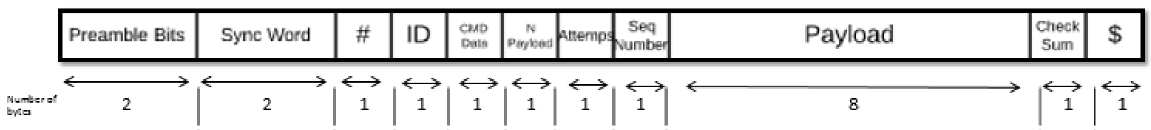


Figure 5.6: Packet Structure implemented

5.3.2 MAC Protocol

There are several aspects to take into consideration, to deploy a more energy efficient communication protocol between the nodes. The MAC protocol represents an important factor in terms of network organization.

An **asynchronous MAC** protocol with a star topology offer simplicity and energy efficiency. The following diagrams show the behavior of the MAC protocol implemented.

Figure 5.7 represents the messages passing between two Sensor Nodes and the Sink Node. Each Sensor Node will communicate asynchronously to the Sink Node.

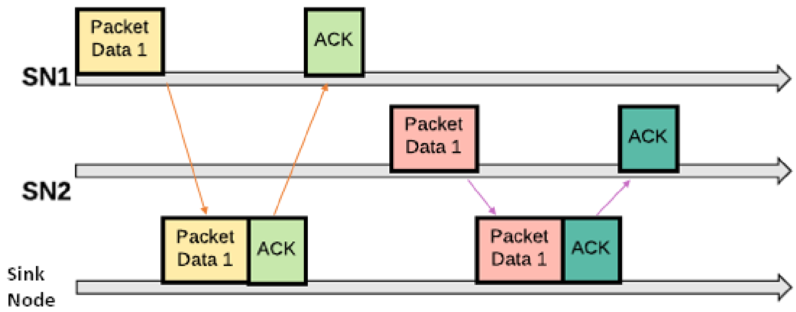


Figure 5.7: Sensor Nodes and Sink Node communication

Figure 5.8 shows a time scheduling between the Sensor Node and Sink Node, when the transmission and receiving messages is successfully accomplished. During active mode, or called wake up time, the Sensor Nodes gets the data from sensors and a packet is prepared to be sent with the updated data. The Sink Node, once received the packet, sends an ACK message. If received by the sensor node, it goes to sleep mode. The sleep mode period is defined by a *RandomSleepTime()* which will be detailed in the next section.

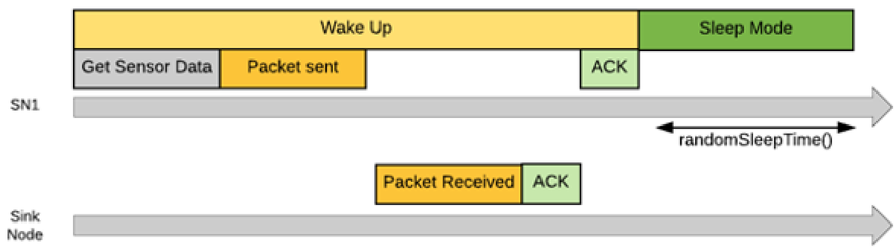


Figure 5.8: Messages successfully passing between the Sensor Node and Sink Node

Figure 5.9 represents the situation when a packet is not properly received, this way, the Sink Node sends a NACK message. The Sensor Node will receive the NACK message and repeat the packet retransmission. Every time the Sensor Node transmits a packet, it waits a time-out threshold, to receive an ACK or NACK, otherwise, will retransmit the packet for a maximum number of attempts.

The timeout defined was 5 seconds, only to test the network behaviour. To clarify, 5 seconds is not a plausible value for a timeout in this network, however it was implemented to verify the messages passing between the sink node and one sensor node. In the same way, the maximum number of attemps defined was 10, only for a matter of testing. It was not studied or analyzed which is the favorable maximum number of attemps, as well the timeout period.

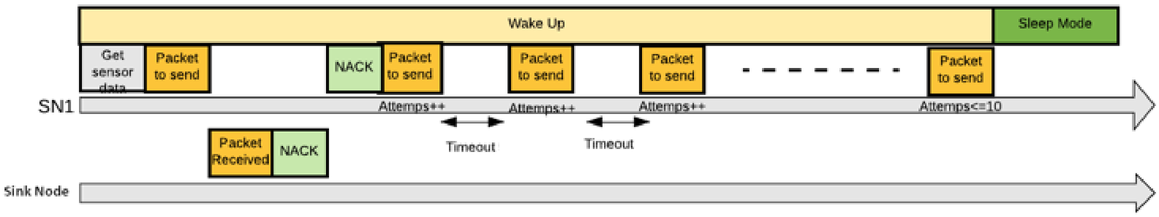


Figure 5.9: Messages passing between the Sink and Sensor Node in the worst situation.

However, following is estimated the time delivering messages .

Time delivery packet It is important to know how much time is needed to transmit the different messages, in order to evaluate the power consumption of the network.

It was used 250kBaud for communications for two reasons: it allows faster transmission, and it will decrease time slot of time to transmit a packet. Consequently, the probability to collide with other packets will also decrease.

Equation 5.2 allows to estimate the time that a message needs to reach the receiver, P_{dt}, Packet delivery time, which is the sum of T_t, Transmission time, and P_d, Propagation delay. Table 5.2 shows the time needed to delivery the different packets, Data and Acknowledgment messages, for a 100m distance.

$$P_{dt} = T_t + P_d = \frac{PacketSize}{DataRate} + \frac{Distance}{PropagationSpeed}^{1} \tag{5.2}$$

Message	Td	Pd	Time to Delivery a Packet (100m)
Data	0.6ms	0.3us	0.6003 ms
ACK/NACK	0.28ms	0.3us	0.2003 ms

Table 5.2: Time Delivering messages, based on Equation 5.2 to 100 m in Distance

There are two situations that can happen, as mentioned before. If the packet is successfully received by the first attemps, the maximum time that the radio will be in transmission mode is given by the Equation 5.3. This way, the maximum time in Tx mode in the best case is around 0.6ms.

$$T_{best} = T_{dataSsensors} + T_{TdACK} \tag{5.3}$$

In the worst case situation, if a Sensor Node, can not communicate with a Sink Node even after 10 attempts, the module will switch between Tx and Rx. This way, the maximum time in Tx/Rx mode is the sum of 10 attemps trying to send the same packet, 10 NACK messages and the timeout it waits in Rx mode that was predefined as 5s. Equation 5.4 shows the sum

[1] In wireless communication, the propagation speed, is the speed of light 3.0 10^8 m/s . Once it will be applied for small distances, the result of the second fraction can be considered zero.

of all period that the radio can be activated, resulting in 58 seconds wasted in the most power consumption modes.

$$T_{worst} = 10 * T_{TdData} + 10 * T_{TdNack} + 10 * T_{TimeOut} \tag{5.4}$$

In order to reduce the Timeout threshold, as so the probability of collisions, a function that generates random Timeout slots of time is also implemented. It generates timeout intervals between 20ms and 5 seconds. The reason of the chosen interval is only a matter for testing the network.

As mentioned before, a **Random Sleep Function** reduces the probability of collisions between sensor nodes, once it produce different sleep times and timeout periods. This way, the sensor nodes wake up randomly and independently of others.

As presented in Chapter 2.2.1, is part of the requirements that each sensor node acquires and sends information every hour. There are no restriction on a specific sequence order of the sensor nodes, or restricted time. As a result, the RandomSleepTime() function implemented returns a time between 55 to 65 minutes, which is the time that the Sensor Node will be in Sleep Mode till the next data acquisition.

Probability of collision The probability of two sensors transmitting in the same time slot in a 10 minutes interval is calculated. Knowing that the transmission and reception of data by each sensor node occupies the channel for 8ms, counting on the data transmission and reception of the ACK.

The total number of time slots available, for a period of 10 minutes, are given by the Equation 5.5:

$$T_{Smax} = \frac{TotalTime}{MaximumTime}(s) = \frac{600}{8.10^{-3}} = 75000 \tag{5.5}$$

The non-collision probability, Equation 5.6, P_c is given by independent events [68], and n, is the total number of nodes.

$$P_{nc} = \prod_{1}^{17}\left(\frac{T_{Smax} - n + 1}{T_{Smax}}\right) \tag{5.6}$$

The probability of non-collision of 17 nodes is 99.8 %¸ in a window of 10 minutes.

In Figure 5.10 shows the probability of non-collisions increasing as increasing the time window, as expected. The results were obtained by applying Equation 5.6 for different windows time and number of sensor nodes. Independent probabilities means that each event probability does not effect the probability of other event occur. It is calculated the probability of non-collisions for a higher number of nodes, which shows that the probability of collision for window of 10 minutes is around 0.02, so, it is possible to conclude, that even for 55 nodes communicating in the network, the probability of collisions between nodes is still very low.

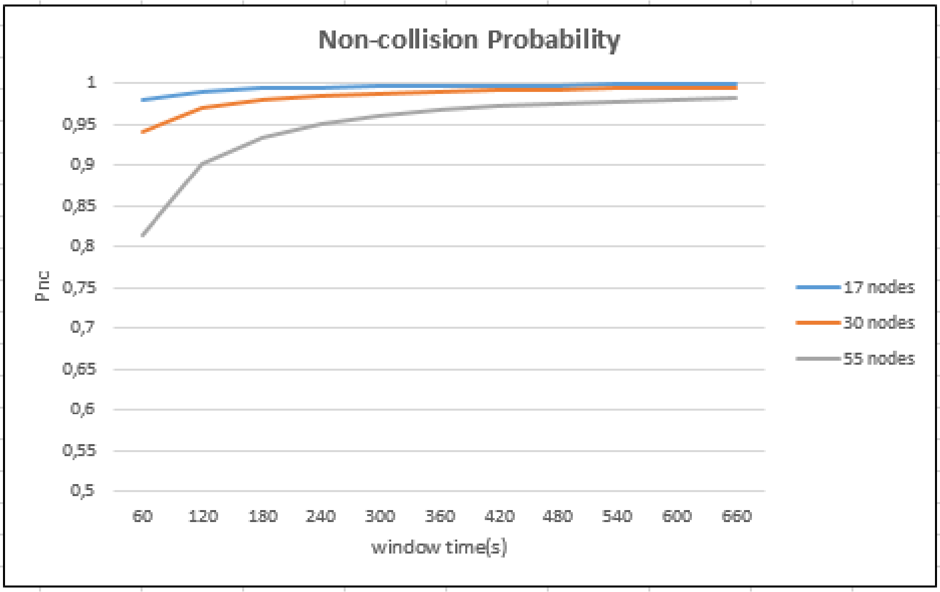


Figure 5.10: Probability of non-collision depending on the number of nodes

5.3.3 State Machines

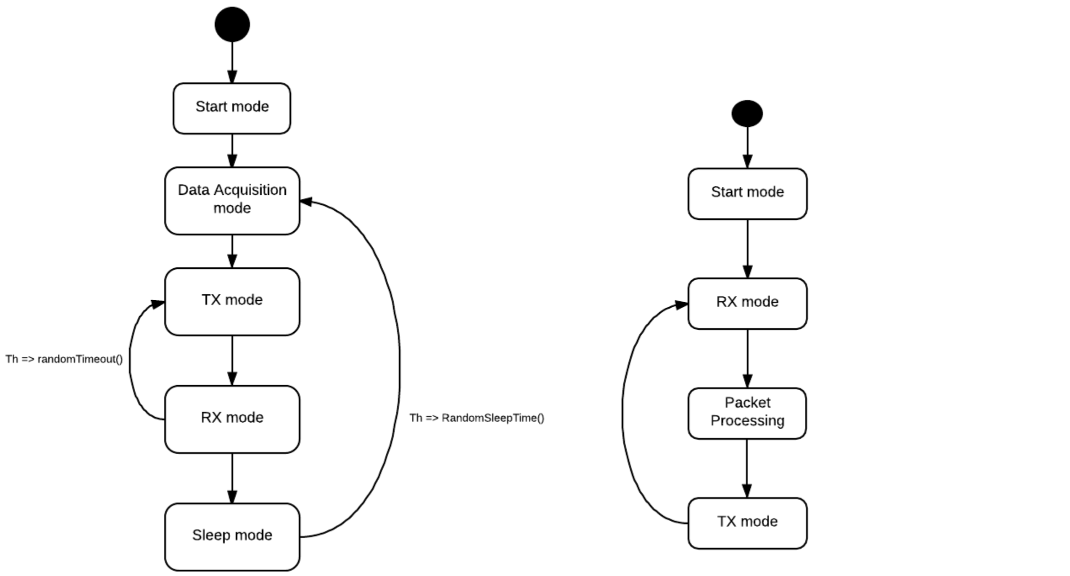
In this section are presented and explained the state machines implemented.

Once the state machine for the Sink and Sensor Node share the same functions in Start, RX and TX mode, it will be only described the State Machine of the Sensor Node. Figure 5.11 shows the both state machines, which represent the organization of the developed code for both nodes. The sink node is divided into four states. It is always in active mode, in receiving mode waiting for packets to process them.

The structure of the sensor node code is divided into five states. Each state is explained in detail below. The transition between Sleep Mode and Data Acquisition mode depends on the value generated by the *RandomSleepTime()* function. The transition from Rx to Tx mode results from the expiration time for acknowledgment messages, which is also generated from a random function. Transitions in the sensor node state machine are programmed to reduce the time in active, Tx and Rx mode, once they require more energy consumption. On the other hand, the state machine of the sink node never leaves the active mode, once the power consumption is not taken into consideration.

It is also presented a class diagram, represented in Figure 5.12, which shows the implemented functions in each state. Next, each class is briefly explained.

Start Mode The clock is set to 26MHz, the higher oscillator frequency offered by the CC1110 SoC, to run the active mode process. The UART is set to allow debugging output messages. Table 5.3 presents the RF-parameters configured, as previously justified, the base frequency selected is 433MHz. The maximum space channel allowed in this band is around 199.95 kHz. After testing the different modulations formats that the CC1110 offer, the GFSK format showed a better performance, and because of that, it was the selected one. The data-



(a) State machine of the Sensor Node

(b) State machine of the Sink Node

Figure 5.11: State machines

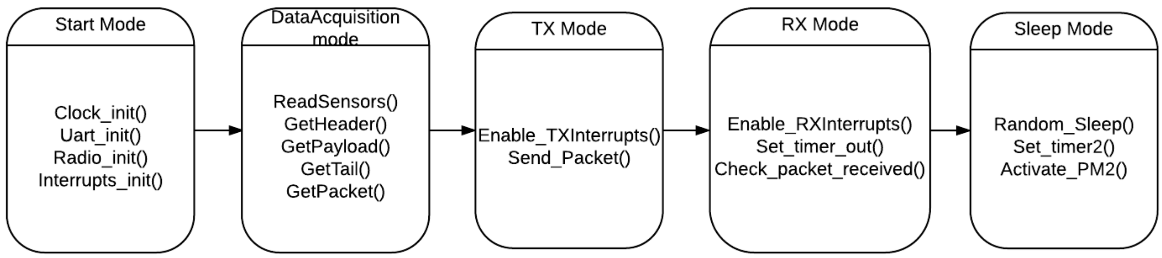


Figure 5.12: States and Classes Diagram

rate performance was also tested, and 250kBaud presented better results. Higher data-rates also allows fast communications and lower probability of collisions. It was selected 10dBm as output power, once it provides more power to higher ranges.

Base Frequency	Channel Spacing	Modulation Format	Data Rate	TX Power
432.99 MHz	199.95 kHz	GFSK	249.93 kBaud	10 dBm

Table 5.3: RF parameters used to configure the transceiver

The CC1110 module offers eighteen interrupt sources, which nine of them are used, such as RF TX/RF done, Timer Overflow, RF general interrupts flags. In the Start Mode, all interrupts registers are configured. Once some of them share the same interrupts flags, they must be individually enabled or disable.

Data Acquisition Mode This mode includes the functions deployed to read the data from sensors. The implemented code was previously described.

The *ReadSensors*() reads the DHT11 sensor, which result in a temperature and humidity value. The reading process of sensors requires a significant amount of energy, and because of that, it is only read one time, and data is saved in a buffer and updated on for the next sample.

The *GetHeader*() function is updated every time a packet is transmitted. In case of a retransmission packet, an update of the packet must be done. The sequence number, attempts, and checksum bytes are updated.

The *GetPayload*() function organizes the payload field with a byte which identify each sensor and the respective measured value.

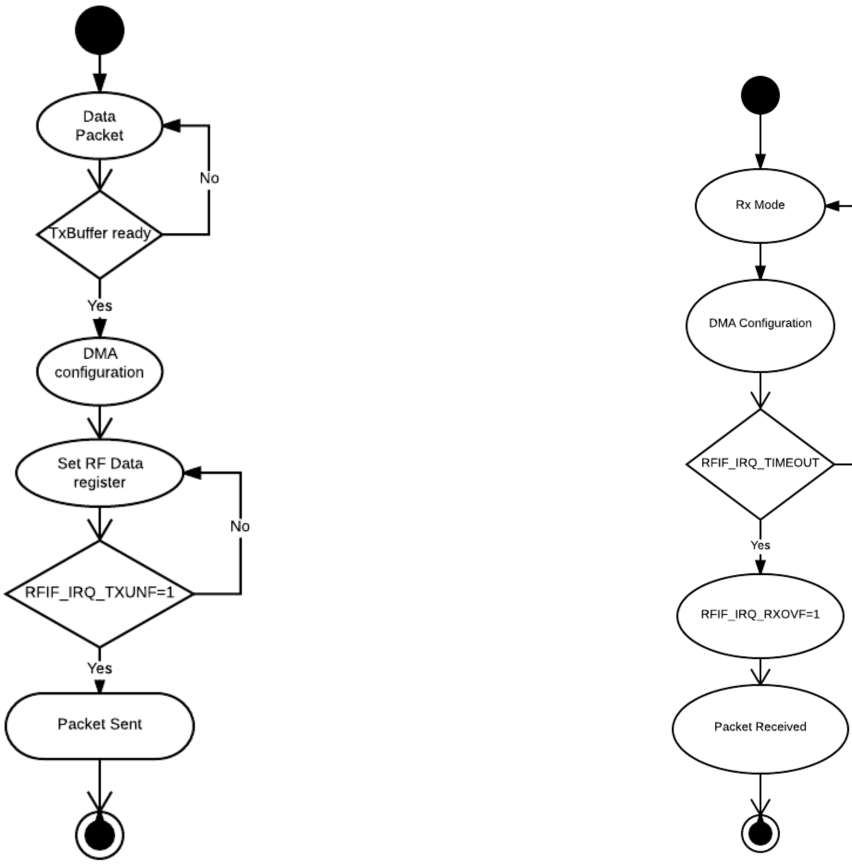
The *GetTail*() returns the sum of all bytes from payload field, which represent the CheckSum byte.

Lastly, a *GetPacket*() function organizes the packet structure proposed as shown in Figure 5.3

Tx Mode To transmit data, a few registers and interrupts must be set, as Direct Memory Access (DMA) and RF TX/RX interrupts flags. Figure 5.13a briefly presents the transmission data process. The MCU offers two options to configure the data to transmit. It can be written to the RF Data registers as a 1byte First In First Out (FIFO), or, it can be implemented a DMA configuration to transfer data directly between the FIFO and the RF Data registers. The functions *EnableTXInterrupts*() and *SendPackets*() are responsible to set each DMA register, such as the TxBuffer length in bytes, the destination address, the interrupt mask, the DMA priority and DMA channel.

RX Mode Figure 5.13b shows the main registers and interrupts that are set to enter to receiving mode. When this mode is required, the DMA is configured to prepare the radio to synchronizing with the Preamble bits and Sync word from other radios. The main difference between the DMA configuration in RX and TX mode, are in the memory registers used. The function *Set_timer_out()*. The RF register, RFIF_IRQ, is configured to generate an interruption if some packet is received. If any packet is received and the timer expires, the Rx process is done, without success. Otherwise, if a packet is successfully received, the bytes are saved in a RxBuffer.

Sleep Mode The Sleep Mode state intends to be the most power efficient as possible. The function that generate a random value between two intervals pre-defined by the user, as mentioned before, are the first steps of the Sleep Mode. The lowest frequency clock, 32.768KHz is configured. It was set the PM2, which offers a low power consumption of 0.5uA and can be used a timer instead of an external interruption to wake up from the Sleep Mode. The timer expires and an event is generated.



(a) TX Mode state process **(b)** RX Mode state process

Figure 5.13: TX and RX state processes with interrupts and registers configuration

5.3.4 Packets Processing

The aim of monitoring a *Salicornia* plantation is to acquire a significant amount of data to allow that biologists are able to have conclusions about the growth and survival of the plant. Because of that, Sink Node is responsible to process all packets received and separate the different packets by sensor node ID and then by the different data sensors. Figure 5.14 presents how the sink node process the received packets.

After detected if the received packet is from the network, they are separated by ID and data sensing. The data is sent using a UART by serial communication to a computer. To read all data from the serial bus, it was used Matlab to save all data into a text file.

5.4 Energy consumption

Through the reference tables presented in the datasheet [69] of the CC1110 module, it is possible to obtain an estimate of the total consumption of Sink and Sensor Node. As mentioned in the datasheet, current drawdowns refer to measurements made for a 3V input

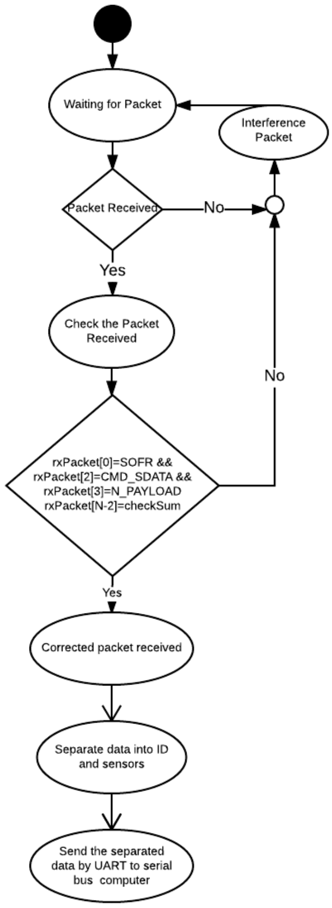


Figure 5.14: TX Mode state process

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voltage at a temperature of 25 °C.

The current consumption values presented in Table 5.4 are taken from CC1110 datasheet. To the Sleep mode, is the same consumption of PM2, and for Tx and Rx mode are the same consumption for that modes if configured 250kBaud data-rate and 433MHz frequency band. It is not presented the period in active mode, spent to read the sensors, once it is a very low period.

As presented before, Table 5.2 shows the periods spent in each mode. This way, it is possible to obtain an estimation of the current consumption for the Sensor Node, considering the time spend by each mode in a cycle of one hour, which is also presented on table for each mode.

The multiplication between the instantaneous consumption of each mode and the respectively cycle, and therefore, the sum of all, results in a current consumption per cycle of 0.21 mA.

$$BatteryLife = \frac{BatteryCapacity(mAh)}{CurrentConsumption(mA))} \tag{5.7}$$

Despite the fact that there was not used a battery to power the modules, once there was

	Current Consumption	Cycle(%)
Sleep Mode	0.5uA	99.86
Tx Mode	33.5mA	0.00004
Rx Mode	20.5mA	0.13

Table 5.4: Instantaneous current consumption and percentage in a cycle of 60 minutes

not available to test the network performance, a battery is suggested, which fits the needs of the module. The 7106101511(VARTA) lithium battery [70] offers 3.6 V and it offers a continuing discharge current of 60mA.

Considering the results of current consumption per cycle, the battery of 2500mAh and the Equation 5.7, results in a battery life period of 11904.76 hours, which correspond to 496 days, which is equivalent to more than 1 year and a month.

In this way, the network is energetically efficient as initially required. The network is able to operate for more than a season.

5.5 Development and deployment costs

One of the main requirements of the project is to be as low-cost as possible in terms of development and deployment. The costs are following presented in Table 5.5. These prices only refer to the cost of the deployment and development along this dissertation. It is also presented a brief research about the cost of each device for a higher number of devices purchased.

In terms of the deployment, some tools are required, such as the evaluation board and modules, cables and a debugger, which cost around fifty euros. Each CC1110, with an antenna included, it costs around five euros. All these expenses were supported by WATGRID company.

	Price/unit €
CC1110	2.30 - 5.04
Deployment Kit	70

Table 5.5: Modules and evaluation board costs [71]

The price per CC1110 module can be very low if required more than one hundred samples, around 2.30 €, as shown in Table 5.5.

The DHT11 sensor costs around 5 €[72] and waterproof box to protect the SoC cost 7 €.

6

Evaluation

6.1 Introduction

This Chapter describes the tests that have been done and presents the obtained results to validate the implement system architecture.

Section 6.2 presents the results obtained to validate the integrated sensor in this project.

Section 6.3 presents the obtained results to validate the MAC protocol implemented in different scenarios.

In Section 6.4 are presented the obtained results about the energy consumption.

6.2 Sensors

To validate the accuracy of the temperature sensor a simple test was performed. There were no laboratory conditions to test all the necessary range, as presented before in Table 2.2. Because of that, the temperature sensor data were compared with the results from a thermometer certified by an accredited laboratory, Fluke Thermometer [73]. Although this method doesn't be the most efficient to validate the accuracy of the sensor, it was not available a proper oven to allow controlling the temperature and humidity to obtain more precise results in the necessary range.

6.2.1 DHT11 results

Figure 6.1 shows the results of temperature read in the same instant from DHT11 and the Fluke thermometer. It is also presented the difference between both values, which represents the absolute error. The higher absolute error obtained is 2.92ºC. This difference can be related with the different response time that Fluke and DHT11 offer. Once it was not a controlled environment, it was not possible to maintain the same temperature to wait for both sensors stabilize. However, the test allowed to verify that the sensor reacts for instantaneous temperatures variations and is near the results obtained by a certified and calibrated thermometer.

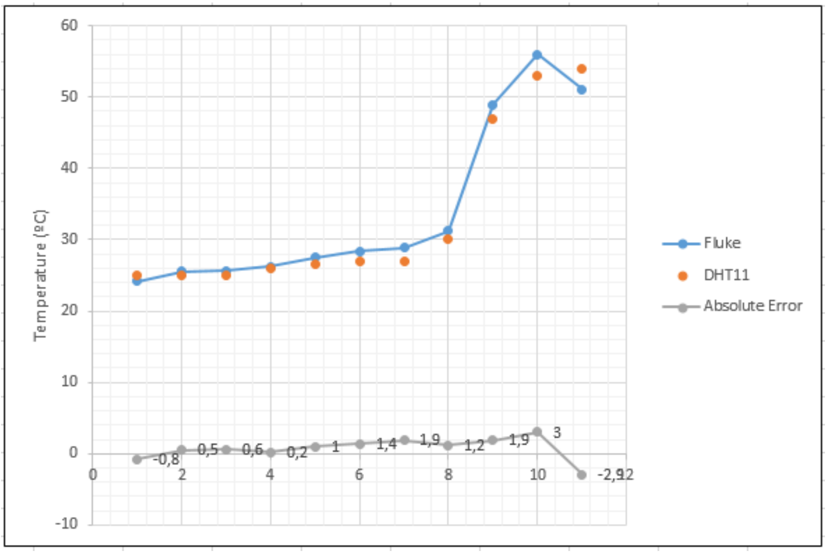

Figure 6.1: Relation between reference temperature (Fluke) and the DHT11 measurements

Once there was not a proper tool to measure the humidity variation, the relative humidity was compared with hygrometer available on the laboratory. It was not possible to change the humidity conditions inside the laboratory, and because of that, it was measured in different days, to verify if the sensor is responding to different humidity conditions, as presented in Table 6.1. The maximum difference between the hygrometer and the sensor was 2 RH, which allows to conclude that the sensor is reading properly although do not allow to conclude about it accuracy.

% RH	**Hygrometer**	**DHT11**
1st Day	58	60
2nd Day	58	58

Table 6.1: Humidity results in Hygrometer and DHT11 sensor

6.3 Network

To verify if the implemented network architecture operates properly, different scenarios and conditions were performed. The following subsections present the results of the tests performed to verify if the implemented code in Sink and Sensor node was being executed as supposed. Although the required number of seventy sensor nodes, only three CC1110 modules were available in the laboratory to test the network.

6.3.1 Modulation Formats

As mentioned in Section 5.2.1, the CC1110 module offers different modulation formats. One of the main goals of the network is to reach the highest distances, and because of that, some initial tests were performed to check the behavior of different digital modulation and baud-rates. These results were obtained with a RF-Smart Studio 7, a software tool, provided by TI, which allows testing different RF parameters. These parameters, such as the base frequency, channel spacing and Tx Power were constant, as mentioned in Section 5.3.3.

These tests were performed in a field near the University buildings.

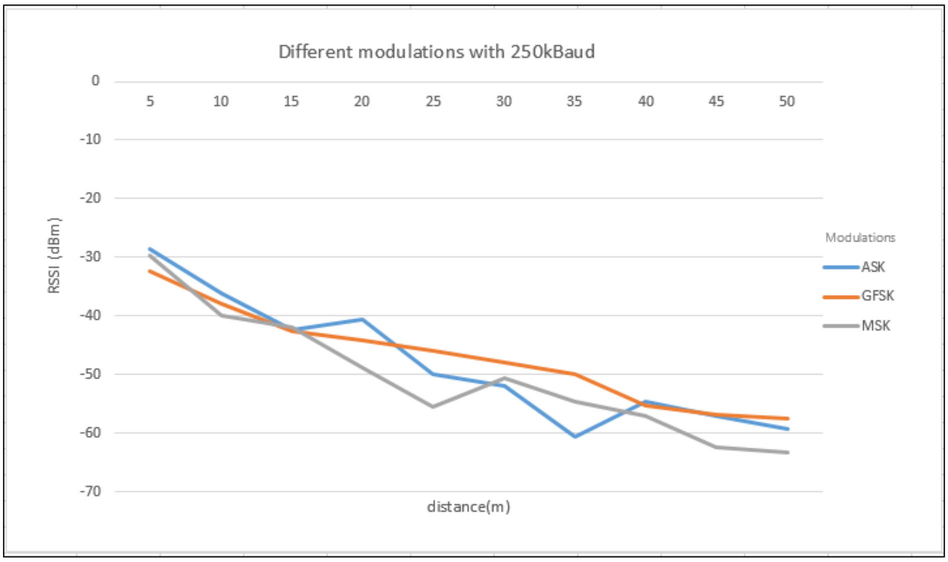

Figure 6.2: Different digital modulation performance with distance

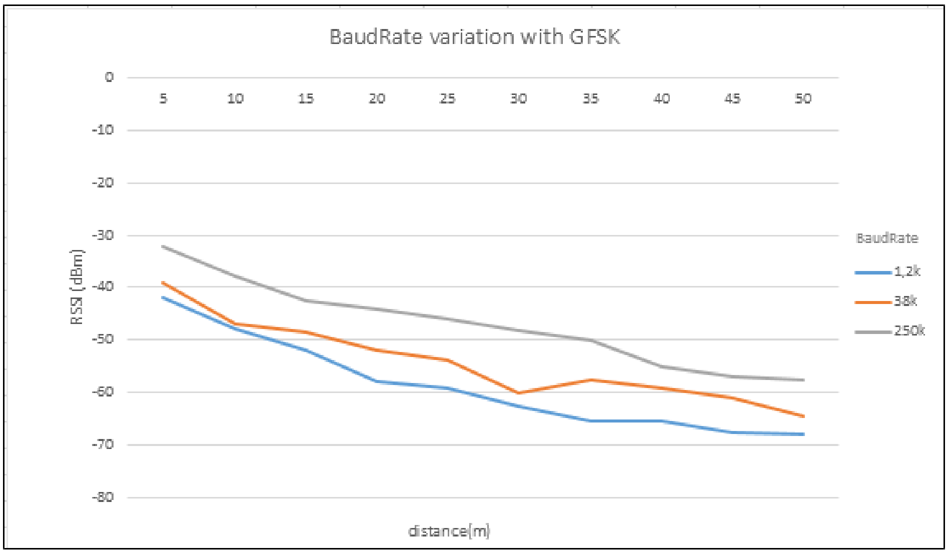

Figure 6.3: Different baud-rates performance with distance

Figure 6.2 shows that the three modulation formats have a similar behavior in distance. The attenuation in dBm with distance shows the power signal decreasing which increases the probability of signal lost between nodes. However, the GFSK modulation format shows to be the one which offers a best performance compared with the other modulations results.

The results presented in Figure 6.3 were performed to verify the transceiver behaviour for different data-rates. To test, packets of 40 bytes were sent from the transmitter to a receiver, placed at a given distance. For each point in distance, it was sent 100 packets to the receiver. The receiver process the packets received and count the packets lost. The SmartStudio allows to obtain the dBm attenuation of the signal received. A lower data rate offers more sensitivity in the receiver and so, a higher range. On other hand, a higher data-rate allows to have faster communications. This test shows that even with a higher data rate, 250k baud-rate, it keeps a good performance in terms of reach.

6.3.2 MAC Protocol Performance

To verify the performance of the MAC protocol some tests were performed in different scenarios.

As mentioned before, the sink node processes the received packets from the sensor nodes. The data packet structure was previously explained and presented in Figure 5.6. By the sequence number of each packet is possible to detect lost packets. The deteriorated packets correspond to the packets which the CheckSum byte do not correspond to the sum of all bytes of the packet received. Counting the number of NACK's and ACK's transmitted allows to identify if the Sink is answering properly to the Sensor Node packet. The Attemps byte correspond to the number of packets retransmissions.

The performed tests allow to conclude about the following network features:

- Packets Successfully Received
- Packets Deteriorated
- Packet Loss
- Packet Interference/Noise
- Packets Received from Sensor Node 1
- Packets Received from Sensor Node 2
- Packet Sequence Lost Sensor Node 1
- Packet Sequence Lost Sensor Node 2
- Number of ACK's sent
- Number of NACK's sent

To verify the network behavior with one and two nodes, in terms of packets collisions, the following tests were performed.

For both tests, some characteristics were the same, such as: They were tested in a laboratory environment which is susceptible to other RF-devices interferences. To obtain faster results, the randomSleepMode() was set to wake up between 50 and 60 seconds to transmit. The sensor nodes were placed for one meter distance of the sink node.

First Scenario The test was performed with one Sensor Node and the Sink Node. The node sensor transmitted 450 packets, and the packets received by the sink node were processed and analysed.

	Sink Node Packets
Packets correctly received	450
Attempts	6
Interference	888
Deteriorated	0
Sequences lost	0
NACK sent	0
ACK sent	450

Table 6.2: Processed packets by Sink Node after 450 packets sent by one Sensor Node

The results obtained are shown in Table 6.2. All packets sent by the sensor node were received by Sink Node, since any sequence number was missing. In total, 6 retries were recorded, which means that in some situations the same packet was retransmitted, which produces a packet loss of 1.3 %. During the sink node listening period, it received 888 packets interference in the surrounding environment. It was count 456 ACK's messages, which allows us to conclude that the sensor node did not detect this message and retransmitted the same packet.

Second Scenario With the same configuration of the first scenario, the same test was performed, but now with two sensor nodes. The total packets sent by each node was 530 and 520, which results in a total of 1050 packets analysed by the Sink node. The results are shown in Table 6.3.

	Sink Node Packets
Packets correctly received	1050
Attemps	61
Interference	1348
Sequences lost	0
Deteriorated	0
From SN1	530
From SN2	520
NACK sent	0
ACKs sent	1050

Table 6.3: Processed packets by Sink Node after 1050 packets sent by two Sensor Node

Even in the second scenario, any sequence number was missed, which means that any data packet was lost. However the number of attempts is higher than the first scenario, resulting in a packet lost of 5.1 %.

The high number of attemps results means that the Sink Node was not able to properly receive the packets from the Sensor node at the first attemps, probably because of others radios interference.

The obtained results shows that the algorithm to process the packets received is working properly.

6.3.3 Range Tests

The range tests were performed in different scenarios. As mentioned in Chapter 2, the area to be covered is near the down-town area but in a zone without buildings, and because of that, is expected a null or very low interference from other communication devices.

The tests were performed with the following characteristics:

- The *RandomSleepTime()* was set between ten and sixty seconds;
- It was tested with two Sensor Nodes and a Sink Node;
- The total packet received from sensors in each scenario;
- The modules were placed one meter high from the ground, as it is shown in Figure 6.5;
- The antenna was placed in vertical position with the ground;
- For each distance point, it was tested fifty packets transmission between the sensor nodes and sink node;

Urban Scenario The first scenario that has been tested, was in an urban area, at the Campus of the University of Aveiro. This area is susceptible to a high interference from other devices once there are buildings around. Figure 6.4 shows the results. The modules were placed ten in ten meters, until 80 meters.

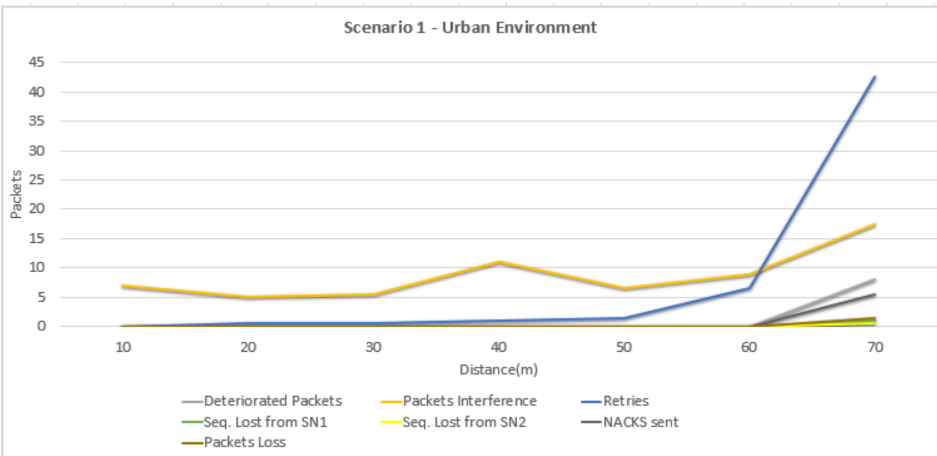

Figure 6.4: Results in Urban environment with higher interference susceptibility

For this scenario conditions, these results show a reach much lower than expected. For seventy meters, the number of retries, which means a maximum of ten attempts for a packet, increases constantly. This way, the probability of a packet be lost also increase. Around this distance, some deteriorated packets were also detected. These deteriorated packets can be a result, for example, two sensor nodes trying to communicate at the same slot of time or from other devices interference.

(a) CC1110 placed in a Rural Scenario

(b) CC1110 placed in a Lagoon Scenario

Figure 6.5: Modules position for performed tests

In a nutshell, the results presented in Figure 6.4 show that an urban environment brings several disadvantages for the network since the packets interference and distance cause a higher packet loss than the expected. In other hand, it was also possible to conclude that the MAC protocol is working as it was proposed.

Rural Scenario The second scenario were performed at a rural area, with a very lower interference expected.

Figure 6.6 shows that the range results have a very different behavior from the urban scenario. For a higher distance, there are no packets lost and the retries number is much lower when compared with the first scenario.

This scenario was tested once it is similar to the real habitat of the proposed requirements. Even in an area without any wireless device communication around, only the modules and two computers, some interference was detected.

The positive results obtained in this scenario brings a strong guarantee about the efficiency of the network in terms of reach and communication quality of the network.

Lagoon Scenario This environment brings some challenges for the WSN. One of them, is the signal attenuation and reflection near water, inside of an enclosure circuit box for circuits. To verify the performance, in terms of range, this scenario was tested near the lagoon of the Ria of Aveiro, as shown in Figure 6.5b. The Sink Node was placed to a distance of 120m from the Sensor Nodes. The sensor node transmitted 500 packets during the test. In this situation,

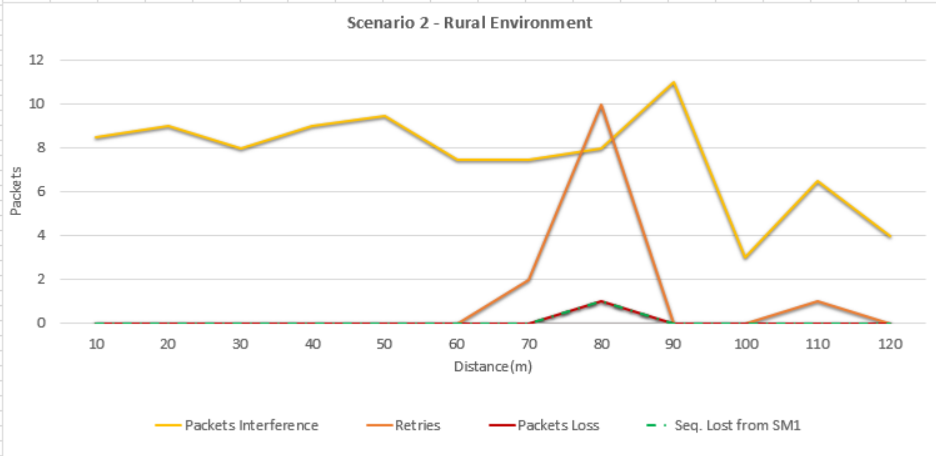

Figure 6.6: Results in Rural environment with lower interference susceptibility

to obtain fast results the randomSleepTime() was configured between 11ms to 34ms. The results are shown in Table 6.4.

	Sink Node Packets
Packets correctly received	500
Attemps	3
Interference	39
Sequences lost	0
Deteriorated	1
From SN1	262
From SN2	238
NACK sent	1
ACKs sent	499

Table 6.4: Results in Lagoon environment for a fixed distance of 120 m

The results shows a good performance in Lagoon environment. The reduction of packets interference is probably related to reduction of idle listening by the Sink node. For 500 packets received in the Sink Node, only 3 packets were lost, which results in a packet loss of 0.6%.

6.3.4 Time delay between nodes

To verify if the Sensor Node sleeps for the supposed time, it was set a timer in the Sink node, to count the time between two packets received in succession, from the same sensor node. As well, a timer was set in the Sensor node, to count the time between two transmitted packets. The objective is to compare the both timers and conclude about the time the sensor node is in sleep mode.

The results are shown in Figure 6.7.

The highest difference obtained between the timers in each node is 4.25us. It is expected a

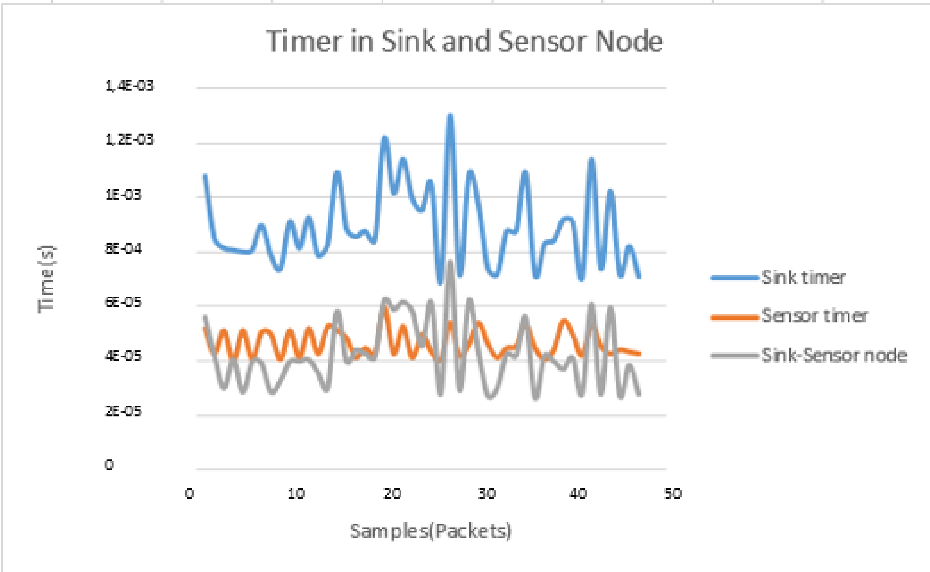

Figure 6.7: Sleeping mode period

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difference between the time sample in each node, because of the jitter in the packet processing and also because of different precision of each crystals in the different modules. The results show that the timer configured to execute the sleep mode during the period calculated by the randomSleepTime() function is working properly.

6.4 Energy Consumption

To verify the power consumption it was used a multimeter Fluke 115 [74], with ammeter scale. It was placed between the power supply and the VDD pin. The measurements were made with the evaluation board, which increases the current consumption because of additional components, such as LEDs and regulators. The results are the average of ten samples in each sample, which are presented in Table 6.5.

	Min(mA)	**Max(mA)**	σ (mA)
Init	20	27	2
Rx	41	45	1
Tx	34	38	1
Sleep	11	16	1

Table 6.5: Results of current consumption in the different states

The results obtained and compared with datasheet values, presented in Section 5.4, are rather different. However, it is expected to have an increase of the instantaneous current needed because of the evaluation board, as justified above. It was supposed to isolate only the CC11110 module and test the current consumption, but a voltage regulator was not available on time. Besides that, it is possible to conclude that different modes requires different energy consumes, as supposed.

7

Conclusion and Future Work

7.1 Conclusion

Since the beginning of this dissertation the aim was to find a low cost and an efficient network to monitor an agriculture plantation, more precisely, a *Salicornia* plant which their growth and survival characteristics are still unknown. Along with this dissertation work, several technologies dedicated to wireless sensor networks were presented. A study of the market showed that there are several technologies that easily answer the needs for a wireless network for agriculture applications. There are many literature presenting the different wireless technologies with their advantages and disadvantages, as well many information about the different hardware that can support sensor and sink nodes in a WSN. There are also many literature and studies which verify the efficiency and quality of service for different technologies, allowing to conclude about the efficiency of each node in different scenarios.

In this moment, LoRa and Sigfox, are the most common technologies which guarantee quality of service and efficiency. Sigfox has the disadvantage of a monthly payment for communications. In the same way, LoRa devices are also an expensive option because of the modules price and the gateway costs. Both were initially presented as a simple and innovative solution. However, it presents costs that are not needed for *Salicornia* application.

Because of that, a lower price solution in terms of hardware devices and without any fixed payment for communications was proposed and implemented to verify it performance.

The RF-transceivers used in this dissertation are a low-cost solution in both situations, once the hardware answer to the processing needs and the communication device allows to achieve the necessary range in ISM bands.

The MAC performance results show that the implemented protocol is efficient. Although the fact that it was only tested with two modules to evaluate the performance, a theoretical study has shown that a lower probability of collisions between devices is expected. The asynchronous MAC solution shows to be a simple solution with several advantages.

The range tests show that different scenarios impact the RF-transceiver performance. In urban environments, the interference from others devices as well the attenuation caused by buildings have a negative impact on the network performance for distances longer than 70 meters. However, with waterproof enclosures, the RF-transceiver performance presents good results in a Lagoon environment up to 150 meter, which is enough for *Salicornia* application. It is important to mention, that for short distances, as it is required for the proposed application, this solution fit the needs, otherwise, the technologies mentioned before would be a better solution for higher distances.

In terms of data acquisition, the implemented program, only processes the packets received with temperature and humidity along the day. Although the used sensors are not the initially intended for this application, it was possible to take conclusions about the SoC adequacy. This one offers the necessary features to run the requirements of a sensor node, such as several GPIO pins, timers, ADC's, UART's, SPI, and other crucial features to develop a sensor node.

The main requirements of the proposed network are accomplished. The results show that the MAC protocol is efficient and power saving. The development and deployment cost of the network are low price. Each sensor node can be supplied by a small battery for a long period, higher than one for one season, as required.

In conclusion, wireless sensor networks bring several engineering challenges depending on the final application. The bunch of technologies that the market offer for these applications, facilitate the developer work given their simplicity in the implementation and deployment. The massive implementation of wireless sensor networks that are getting visibility in the main cities, make the IoT concept valid. However, billions of devices connected will generate several engineering challenges such as in terms of bandwidth usage, power consumption, and security. To answer the bandwidth challenge, some work has been done, and technologies such as IoT-NB and Long Term Evolution (LTE), are being slowly entering the market. In terms of the security challenge, the sensors nodes must be encrypted, once the information can be easily disrupted. In terms of energy consumption, small batteries or eco-friendly solutions, which have been developed, such as in the market for smart sensors.

7.2 Future Work

Throughout this dissertation, some features were detected, which would strengthen the network efficiency. Following some points are noted:

- Implement a data encryption system between the nodes. The CC1110 module offer Advanced Encryption Standard (AES) to perform the encryption/decryption of the packets.
- Test the antenna adaptability to verify if it guarantee the fullest performance of the transceiver.
- Test the network with seventeen sensor nodes.
- Instead of a personal computer as a processing data unit, use an embedded computer to process the data or integrate a gateway as suggested in Section 4.3.4.

- Deploy an interface to acquire the data and display it in real time in an online platform. It is suggested to use platforms such as ThingsSpeak from Matlab, which offer a server to send information in real-time.
- Deploy and implement the device drivers for salinity and soil humidity sensors.
- Test and validate the sensors in the proper conditions, using a humidity and temperature meters certified.
- Develop a PCB layout to add the battery and sensors required to fit in an enclosure box.

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